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Workshop on

Nuclear Reaction Data and Nuclear Reactors: Physics, Design and Safety

13 March - 14 April 2000

Miramare - Trieste, Italy

The OAS

Operator Aid System

G.B. Bruna
FRAMATOME
Paris, France

The OAS
Operator Aid System

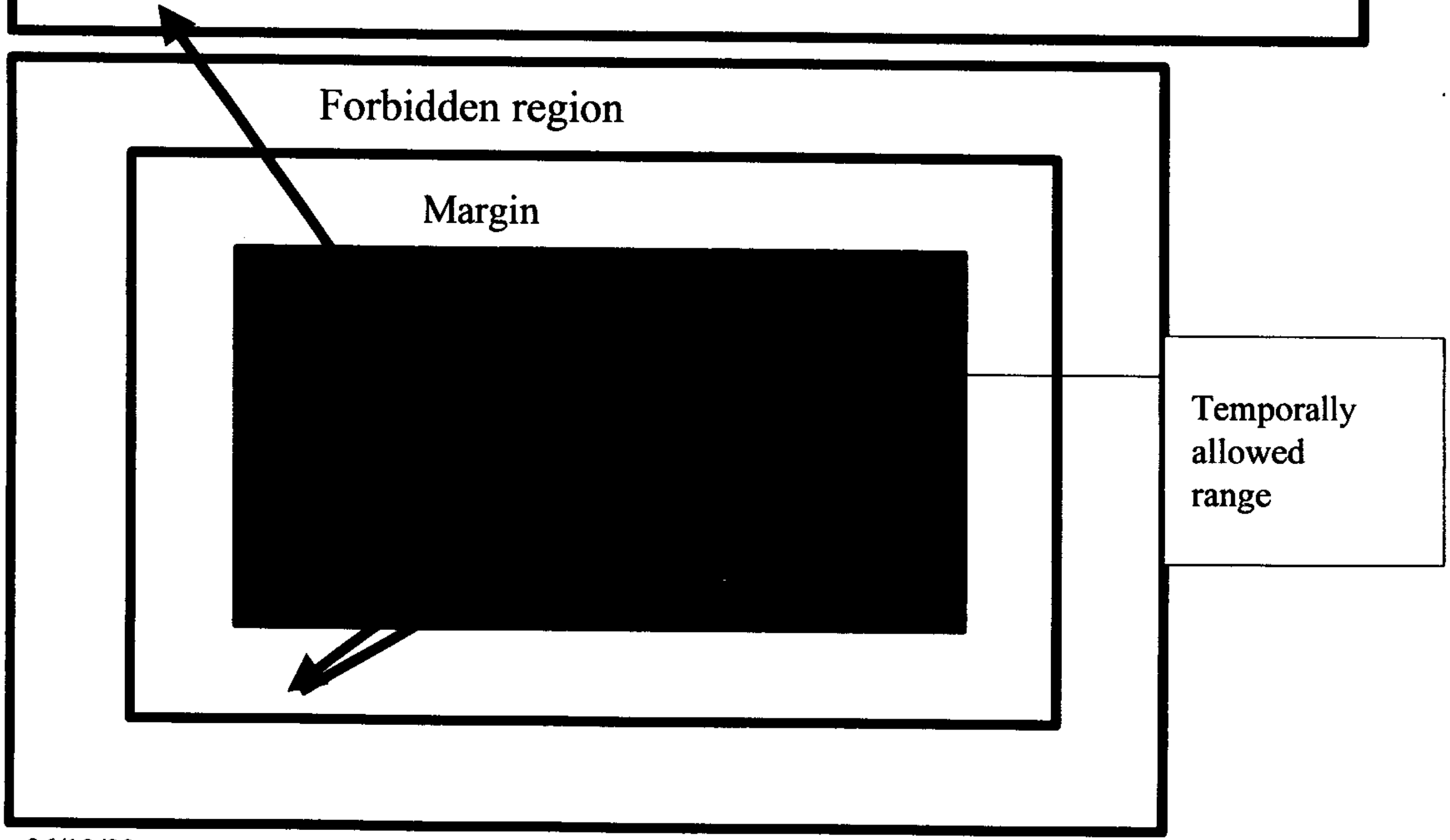
The OAS - Operator Aid System

- Objectives of SAP device (OAS),
- Historical Background and Development,
- Work Underway.

The OAS - Operator Aid System

- Objectives of SAP device (OAS):
  - improve operability of conventional NPPs (load follow capability and capacity factor) adapting the limits imposed to operating parameters to the actual core conditions,
  - optimization of operating margins.

The OAS - Operator Aid System



The OAS - Operator Aid System

- Historical background:
  - SAP device (OAS) is based on an extension of HGPT methodology made in the framework of a collaboration among FRAMATOME, CEA, ENEA and University of Bologna
  - Excerpts were presented at the Saratoga Springs Meeting and are summarized here.

The OAS - Operator Aid System

- Development of SAP device : Excerpts from Saratoga Springs Presentation.

CONTROL SYSTEM WITH PREDICTIVE CAPABILITIES FOR PWR OPERATION BASED ON HGPT METHODOLOGY

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**University of Bologna, Nuclear Engineering, CIRAM, Italy
***ENEA, Energy Department, CRE Casaccia (Rome), Italy
****CEA, SERMA, Centre d' Etudes Nucléaires de Saclay, France

WHEN A CHANGE OF THE REACTOR STATUS IS REQUIRED BY THE NETWORK (E. G., A DECREASE OF THE REACTOR THERMAL POWER RELEASE), THE SYSTEM UNDERGOES A TRANSIENT, WHICH IS GOVERNED BY:

- THE POWER AND TEMPERATURE FEEDBACK,
- THE CONTROL ROD MOVEMENTS,
- THE SOLUBLE BORON POISONING,
- THE SHORT LIFE FISSION PRODUCT POISONING.

AFTER ANY PERTURBATION, AN AUTOMATIC OR SEMI - AUTOMATIC PROCEDURE IS ACTUATED WHICH STABILIZES THE REACTOR SYSTEM ON NEW STEADY STATE CONDITIONS.

NEW SITUATION CAN BE FULLY DESCRIBED BY A BOLTZMANN OPERATOR $\mathbf{B}'$, DIFFERENT FROM THE ORIGINAL ONE BY A QUANTITY $\delta \mathbf{B}$ WHICH ACCOUNTS FOR ALL THE ABOVE MENTIONED EFFECTS.

THE EXTERNAL INTERVENTION TO RESTORE CRITICALITY HAS TO MEET THE FOLLOWING CRITERIA:

- STABILIZE REACTOR POWER,

- MAINTAIN THE AVERAGE CORE TEMPERATURE WITHIN AN AUTHORIZED RANGE,

- FLATTEN THE POWER SHAPE,

- KEEP THE CONTROL ROD CAPABILITY TO SCRAM THE REACTOR OUT.

THESE CONDITIONS CAN BE SATISFIED WHETHER PREDICTING AND CONTROLLING THE ASYMPTOTIC VALUES OF PHYSICAL VARIABLES CALLED « OBSERVABLES », WHICH ARE REPRESENTATIVE OF REACTOR BEHAVIOR.

AN INTEGRATED SYSTEM WITH PREDICTIVE CAPABILITIES, SAP (Système d'Aide à l'OPérateur), CAN BE A MAJOR TOOL FOR A FLEXIBLE OPERATION OF NPPs DURING LOAD FOLLOW.

SUCH A SYSTEM, ENABLING OPERATOR TO FINELY CONTROL POWER PRODUCTION WHILE OPTIMIZING OPERATING CONDITIONS, CAN SIGNIFICANTLY IMPROVE THE NPPs' LOAD FOLLOW CAPABILITIES AND CAPACITY FACTOR.

THIS PREDICTION SYSTEM IS TO BE KEPT FREE FROM PROTECTION TASKS.

WHILE COMPENSATING REACTIVITY EFFECTS OF PERTURBATIONS, IT WOULD HELP THE OPERATOR TO CONTROL OBSERVABLES SUCH AS:

RELATIVE LOCAL POWER,

ASSEMBLY OUTLET RELATIVE TEMPERATURE,

AXIAL OFFSET,

REACTIVITY WORTH OF CONTROL RODS FOR SCRAM.

OBSERVABLES ARE TO BE KEPT WITHIN "SAFE" OPERATING RANGES. TO DO THAT, A REAL-TIME SIMULATOR MUST SUPPLY SUFFICIENT INFORMATION ON THEIR ASYMPTOTIC VALUES IN FINAL CONDITIONS.

- the Relative Local Power, measured by in - core miniaturized chambers, is defined as:

$$\Pi = \aleph \frac{\left\langle \mathbf{I}^{*}, \mathbf{N}\sigma\mathbf{\Phi}_{0} \right\rangle_{\text{chamber}}}{\left\langle \mathbf{I}^{*}, \mathbf{F}_{0}\mathbf{\Phi}_{0} \right\rangle}$$

- the Assembly Outlet Relative Temperature (measured by assembly or cluster thermocouples and proportional to the local power) is defined as:

$$\mathbf{T} = \Re \frac{\left\langle \mathbf{I}^{*}, \mathbf{F}_{0}\mathbf{\Phi}_{0} \right\rangle_{\mathbf{R}}}{\left\langle \mathbf{I}^{*}, \mathbf{F}_{0}\mathbf{\Phi}_{0} \right\rangle}$$

- the <u>Axial Offset</u> (measured by ex - core detectors, periodically calibrated to in - core measurements) is defined as:

$$\mathbf{AO} = \frac{\left\langle \mathbf{I}^*, \mathbf{F}_0 \Phi_0 \right\rangle_{high} - \left\langle \mathbf{I}^*, \mathbf{F}_0 \Phi_0 \right\rangle_{low}}{\left\langle \mathbf{I}^*, \mathbf{F}_0 \Phi_0 \right\rangle_{high} + \left\langle \mathbf{I}^*, \mathbf{F}_0 \Phi_0 \right\rangle_{low}}$$

- the **<u>Reactivity Worth</u>**, measures in real time the scram capacity of the system when operating in a given control rod configuration. It accounts for the worth of control clusters for reactor scram, when they are already partially inserted into the core for control reasons. It is defined as :

$$\delta(\Delta\rho) = \delta \frac{< \Phi_i^*, \Delta \mathbf{B} \Phi_f >}{< \Phi_i^*, \mathbf{F}_f \Phi_f >}$$

This is not an actual observable of the system, because it cannot be measured by devices.

WORK PERFORMED DURING THE PROJECT

generalizing the HGPT methodology, developed by Gandini in the '80 and applied previously to a finite difference scheme to a mixed-dual computational environment within the CRONOS code, as explained by a companion paper in this conference.

describing physical observables relevant to PWR operation as ratios of functionals linear in the flux and develop a HGPT formulation of their values in asymptotic conditions after perturbation,

deriving an extrapolation formula, to be used for any practical application, which accounts for higher order corrections without computing them explicitly,

defining a 3D reactor sample representative of a real PWR for validation purposes,

checking against direct calculations the whole results of the proposed methodology applied to this sample in several representative cases,

making a statistical compilation of results.

THEORY

The general equations governing the neutron flux Φ distribution and the poison concentration $\mathbf{c}_p$ density of a reactor system can be written (assuming all neutrons are born prompt):

$$\frac{\partial \Phi}{\partial t} = \mathbf{B}\Phi$$

$$\frac{\partial \mathbf{c}_p}{\partial t} = \mathbf{E}\mathbf{c}_p + \mathbf{G}\Phi$$

$$< \mathbf{c}, \mathbf{S}\Phi >_{syst} - \mathbf{W} = \mathbf{0}$$

where the term $\mathbf{G}\Phi$ accounts for the poison production as fission product, whereas $\mathbf{E}\mathbf{c}_p$ accounts for the poison removal by neutron absorption, or decay. The Boltzmann operator **B** depends on density $\mathbf{c}_p$ and an implicit control variable ρ. It depends also on the fuel isotope concentration c, which here, according to a very short time scale, is assumed constant so that is derivative can be neglected. Evolution matrix **E** depends on the neutron flux Φ. This equation depends on constraints on the power history W, too.

ASSUMPTIONS

- the change of fuel nuclides and poison concentrations is negligible in the period of interest;
- reactor is critical both in the initial and final conditions. Any reactivity change engendered by perturbations is compensated by a "critically - reset" actuated either by the operator or the piloting system;
- the Boltzmann operator of the reactor system **B** is linearly dependent on the parameters $p_j (j = 1,2,\ldots,J)$ describing the reactor state thus secondary feedback effects (Doppler and temperature) engendered by perturbations and "criticality reset" are neglected.

According to these assumptions, the state system is reduced to a single linear equation, where subscript 0 accounts for initial conditions. This equation contains a generic reset term to restore criticality. This term is part of operator $\mathbf{B}_0$.

Criticality can be theoretically restored in three different ways: changing the fuel enrichment (worthless in practice), varying the soluble boron concentration in the primary leg or moving the control rods relative to one another.

A specific reset formulation corresponds to every control strategy. For the present formulation the classical $\lambda = (1-\rho)$ reset has been adopted:

$$\mathbf{B}_0 \mathbf{\Phi}_0 = \left[\mathbf{A}_0 + \mathbf{L}_0 - \mathbf{S}_0 - (1-\rho)\mathbf{F}_0\right]\mathbf{\Phi}_0 = 0$$

were **A**, **L**, **S** and **F** are absorption, leakage, scattering and fission operators respectively.

Any physical observable of interest Q can be written as a ratio of functionals linear in the flux. Its general expression is:

$$Q_0 = \frac{\left\langle \mathbf{h}_1^* \mathbf{I}^*, \boldsymbol{\Phi}_0 \right\rangle}{\left\langle \mathbf{h}_2^* \mathbf{I}^*, \boldsymbol{\Phi}_0 \right\rangle}$$

where the generic operator $\mathbf{h}_i^*, (i = 1,2)$ represents here any sub-operator of the Boltzmann's.

According to GPT, the importance function Ψ^* relative to Q observable is defined by the (linear) equation:

$$\mathbf{B}_0^* \boldsymbol{\Psi}^* = \mathbf{s}^* = \frac{\mathbf{h}_1^* \mathbf{I}^*}{\left\langle \mathbf{h}_1^* \mathbf{I}^*, \boldsymbol{\Phi}_0 \right\rangle} - \frac{\mathbf{h}_2^* \mathbf{I}^*}{\left\langle \mathbf{h}_2^* \mathbf{I}^*, \boldsymbol{\Phi}_0 \right\rangle}$$

The source term $\mathbf{s}^*$ is orthogonal to the fundamental mode $\boldsymbol{\Phi}_0$, which, according to the Freedholm alternative, implies this equation to have a unique solution, defined in a space which is orthogonal to the fundamental mode.

IN LOAD FOLLOW, SIGNIFICANT OFFSET EFFECTS CAN OCCUR SO THAT FIRST ORDER GPT METHODOLOGY IS GENERALLY NOT ADEQUATE.

SECOND OR HIGHER ORDER TERMS ARE REQUIRED IN THE PERTURBATION EXPANSION, WHICH FORCES THE USE OF DERIVATIVE FUNCTIONS.

ASSUMING THAT OPERATOR B_0 IS PERTURBED BY ANY VARIATION OF ONE OR SEVERAL PARAMETERS $p_j (j=1,2,\dots,J)$, THE SECOND ORDER PERTURBATION EXPRESSION OF THE OBSERVABLE Q IS:

$$Q_0' = Q_0 + \sum_{j=1}^{J} \frac{\partial Q_0}{\partial p_j}\delta p_j + \frac{1}{2!}\sum_{i,j=1}^{J} \frac{\partial^2 Q_0}{\partial p_i \partial p_j}\delta p_j \delta p_i + O(3)$$

$$Q_0' = Q_0 + \underbrace{\sum_{j=1}^{J} Q_0 \left(\left\langle \delta s_j^*, \Phi_0 \right\rangle - \left\langle \Psi^*, \frac{\partial B_0}{\partial p_j} \Phi_0 \right\rangle \right) \delta p_j}_{\text{first order}} +$$

$$+ \underbrace{\sum_{i,j=1}^{J} Q_0 \left(\frac{1}{2} \left\langle \delta s_{ij}^*, \Phi_0 \right\rangle - \left\langle \Psi^*, \left[\frac{\partial B_0}{\partial p_j} \frac{\partial \Phi_0}{\partial p_i} - \frac{\partial p}{\partial p_j} \left(\frac{\partial B_0}{\partial p} \frac{\partial \Phi_0}{\partial p_i} + \frac{\partial^2 B_0}{\partial p_i \partial p} \Phi_0 \right) \right] \right\rangle \right) \delta p_j \delta p_i}_{\text{sec ond order direct term}} -$$

$$- \underbrace{\sum_{i,j=1}^{J} Q_0 \left(\left\langle \delta s_j^*, \Phi_0 \right\rangle - \left\langle \Psi^*, \frac{\partial B_0}{\partial p_j} \Phi_0 \right\rangle \right) \cdot \left(\frac{\left\langle \frac{\partial h_2^*}{\partial p_i} I^*, \Phi_0 \right\rangle - \left\langle h_2^* I^*, \frac{\partial \Phi_0}{\partial p_i} \right\rangle}{\left\langle h_2^* I^*, \Phi_0 \right\rangle} \right) \delta p_j \delta p_i}_{\text{sec ond order mixed term}}$$

$$\delta s_j^* = \frac{\frac{\partial h_1^*}{\partial p_j} I^*}{\left\langle h_1^* I^*, \Phi_0 \right\rangle} - \frac{\frac{\partial h_2^*}{\partial p_j} I^*}{\left\langle h_2^* I^*, \Phi_0 \right\rangle}$$

$$\delta s_{ij}^* = \frac{\frac{\partial^2 h_1^*}{\partial p_i \partial p_j} I^*}{\left\langle h_1^* I^*, \phi_0 \right\rangle} - \frac{\frac{\partial^2 h_2^*}{\partial p_i \partial p_j} I^*}{\left\langle h_2^* I^*, \phi_0 \right\rangle}$$

ACCORDING TO THE PHYSICAL MEANING OF THE GENERALIZED « IMPORTANCE » FUNCTIONS, THE HIGHER ORDER CONTRIBUTIONS TO ASYMPTOTIC VALUES OF OBSERVABLES AFTER PERTURBATION DEPEND EXPLICITLY ON PERTURBATION ITSELF, WHILE THE ZERO AND FIRST ORDER TERMS ARE PERTURBATION INDEPENDENT.

THUS, TAKING INTO ACCOUNT HIGHER ORDER CONTRIBUTIONS, MEANS MULTIPLYING THE NUMBER OF FUNCTIONS TO BE CALCULATED AND STORED AS MANY TIMES AS DIFFERENT PERTURBATIONS MAY OCCUR.

THE INDUSTRIAL FEASIBILITY OF A DEVICE BASED ON HGPT METHODOLOGY COULD BE SEVERELY THREATENED BY PROBLEMS OF STORAGE SIZE.

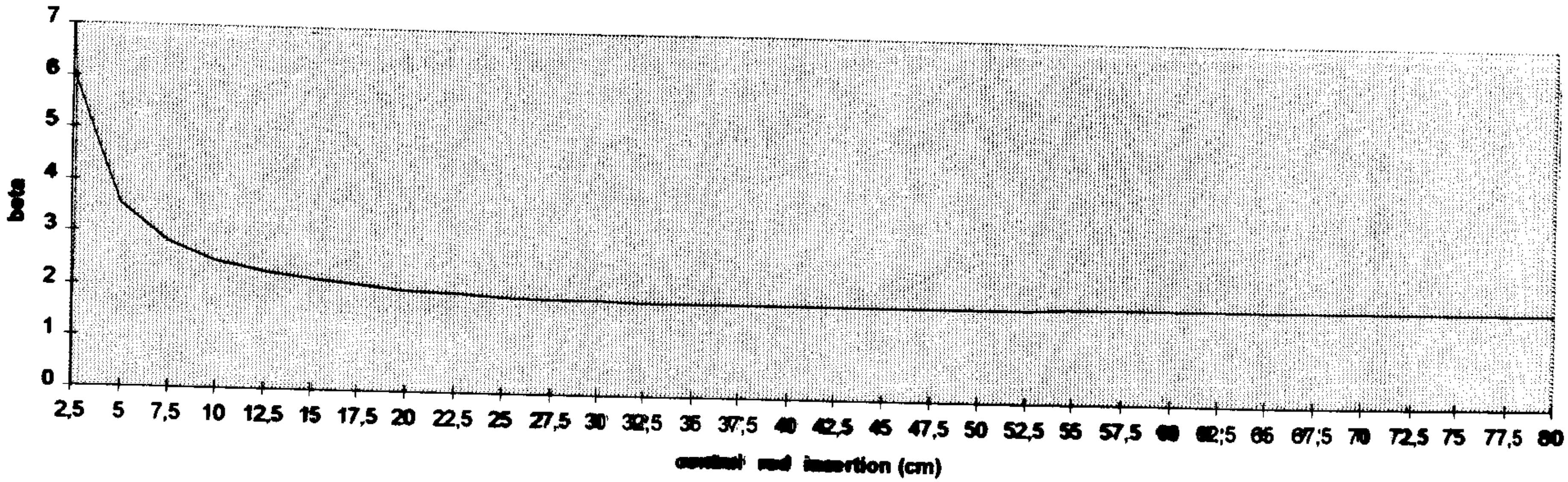
In order to cope with this major problem, an extrapolation formula, based on zero and first order terms only, thus independent on perturbations, has been derived and validated. According to this formula, the asymptotic solution is written:

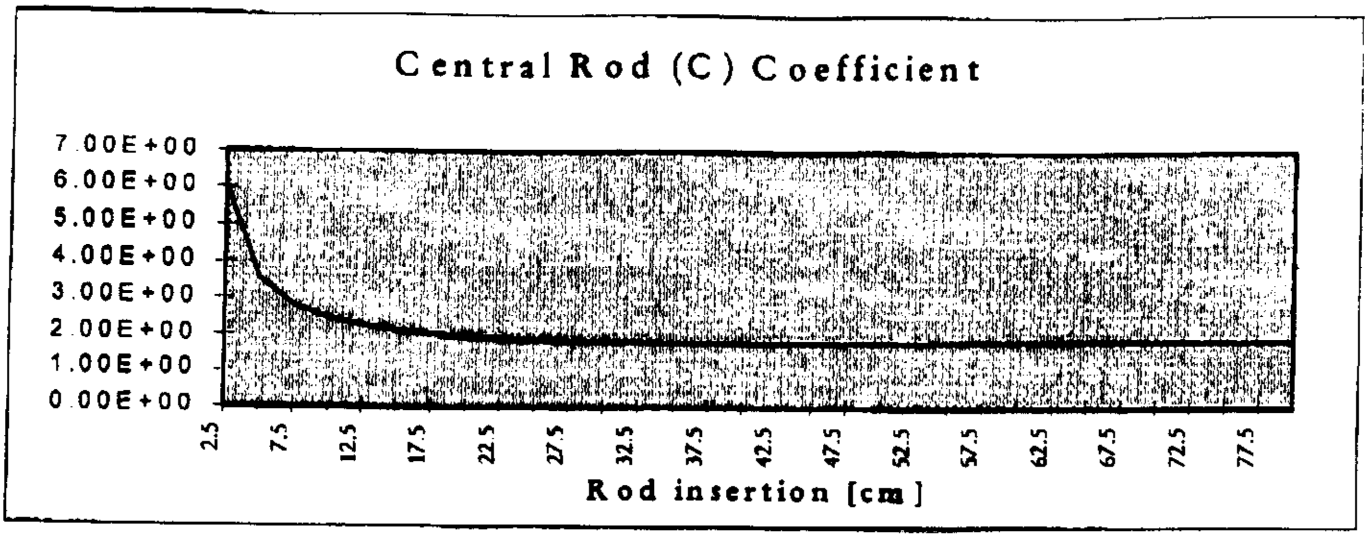
$$\tilde{S}_\infty = \tilde{S}_\infty\left(S_0, S_1, \tilde{\beta}\right)$$

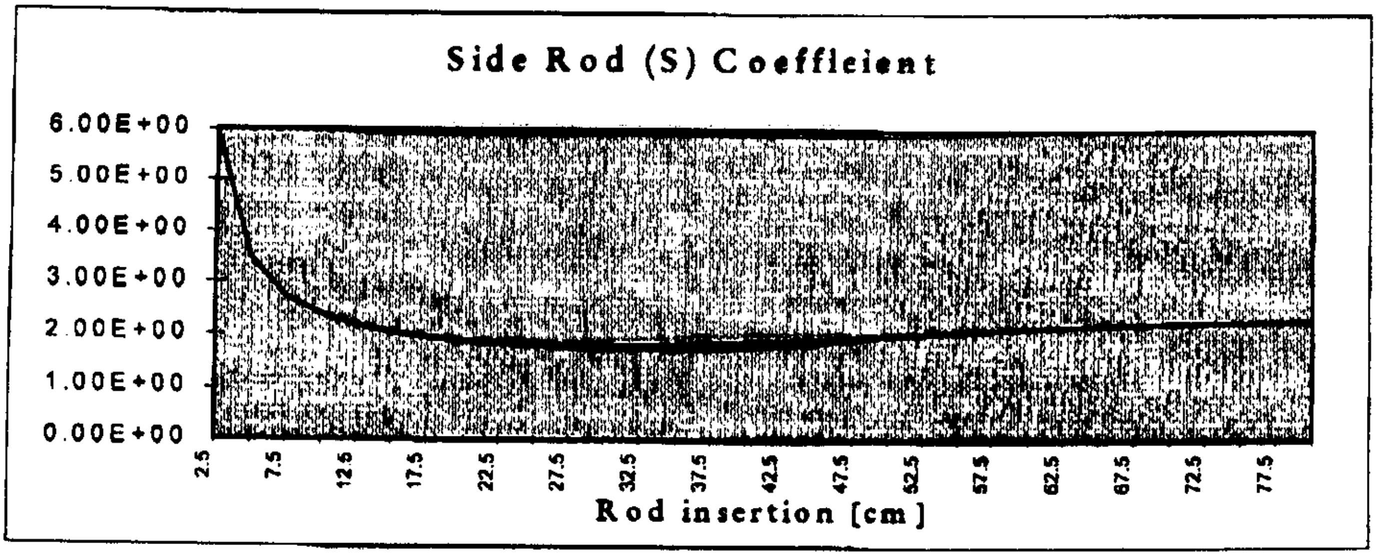
where $\tilde{\beta}$ is a weighting coefficient which takes into account the average contribution of higher order modes (other than zero and first). This coefficient is evaluated as the mean value of a reference set of individual coefficients β^i_{exact} relative to every control device, tabulated once for all.

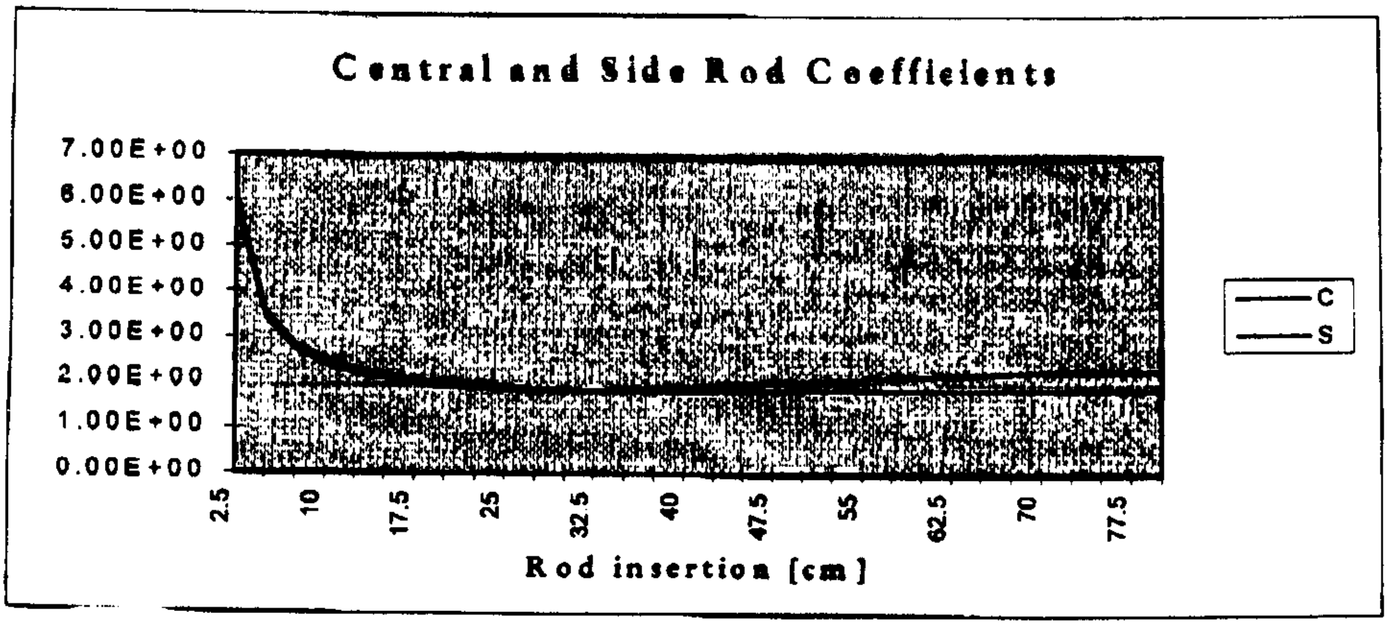
When several devices intervene together, individual contributions are weighted by individual reactivity worth to obtain a unique coefficient.

Coefficients in extrapolation formula




Central Rod (C) Coefficient
7.00E+00
6.00E+00
5.00E+00
4.00E+00
3.00E+00
2.00E+00
1.00E+00
0.00E+00
2.5
7.5
12.5
17.5
22.5
27.5
32.5
37.5
42.5
47.5
52.5
57.5
62.5
67.5
72.5
77.5
Rod insertion [cm]

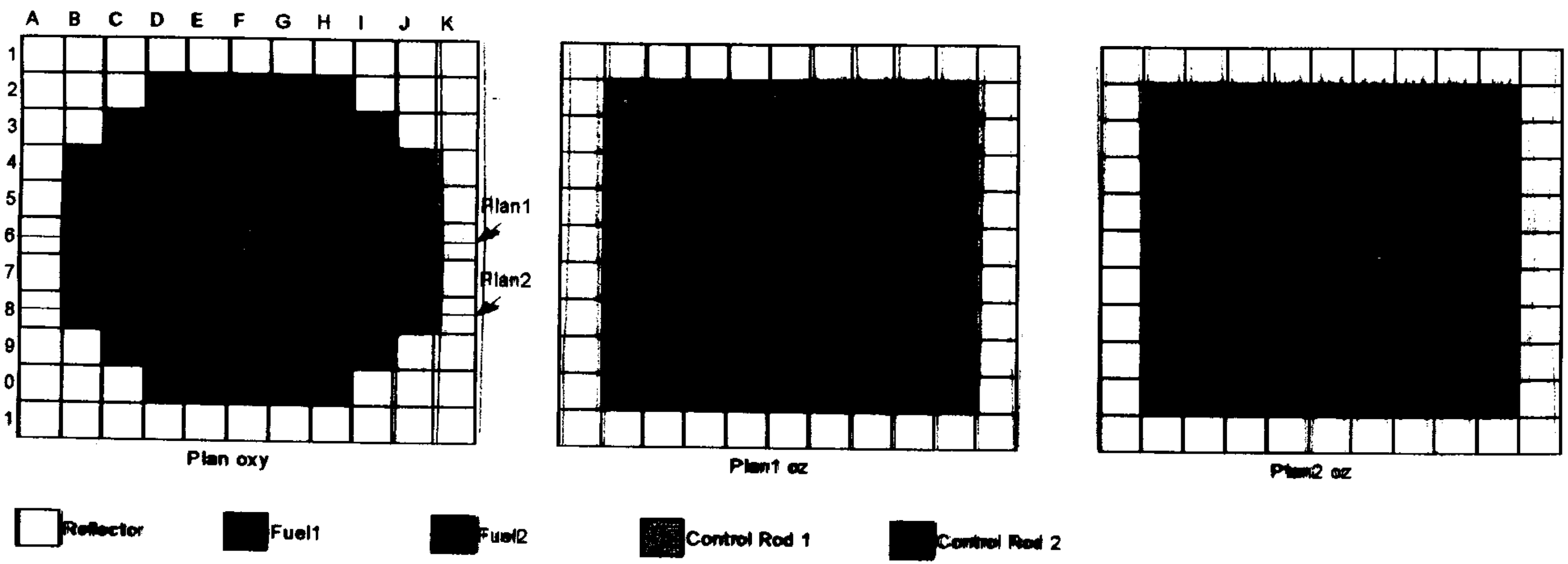

Side Rod (S) Coefficient
6.00E+00
5.00E+00
4.00E+00
3.00E+00
2.00E+00
1.00E+00
0.00E+00
2.5
7.5
12.5
17.5
22.5
27.5
32.5
37.5
42.5
47.5
52.5
57.5
62.5
67.5
72.5
77.5
Rod insertion [cm]


Central and Side Rod Coefficients
7.00E+00
6.00E+00
5.00E+00
4.00E+00
3.00E+00
2.00E+00
1.00E+00
0.00E+00
2.5
10
17.5
25
32.5
40
47.5
55
62.5
70
77.5
Rod insertion [cm]
C
S

NUMERICAL EXAMPLE

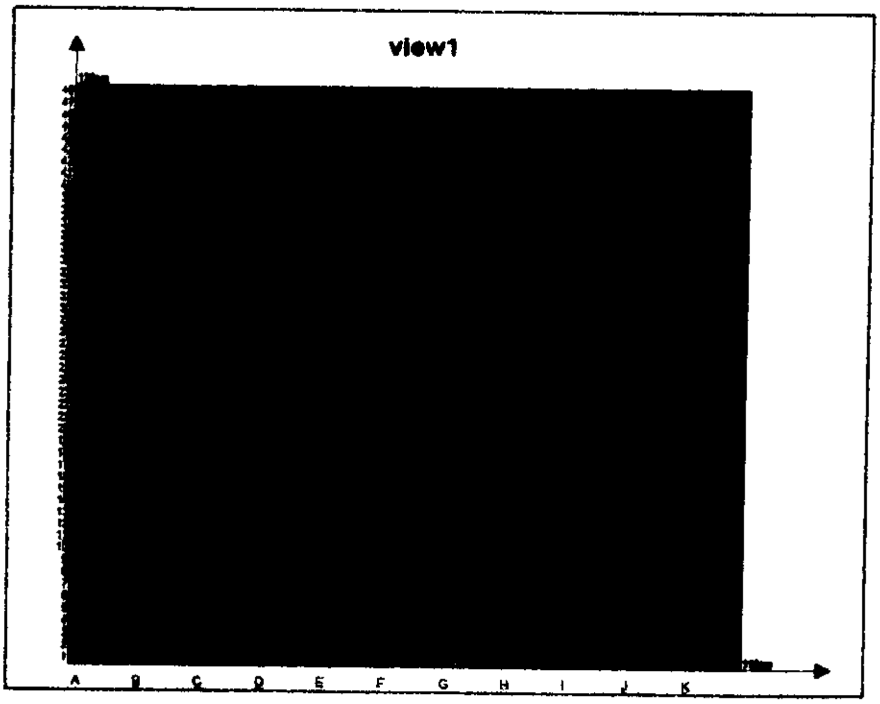
A REDUCED (110 X 110 X 120 CM) SAMPLE REPRESENTATIVE OF A PWR REACTOR HAS BEEN CHOSEN TO CHECK THE METHODOLOGY. THE SAMPLE IS AN HETEROGENEOUS 3D REFLECTED SYSTEM CONTAINING SEVERAL INDEPENDENT CONTROL CLUSTERS. CALCULATIONS ARE PERFORMED IN DIFFUSION APPROXIMATION AT TWO GROUPS. A FINITE ELEMENT NODAL MIXED DUAL METHOD, AS IMPLEMENTED IN THE CRONOS CODE, HAS BEEN USED.

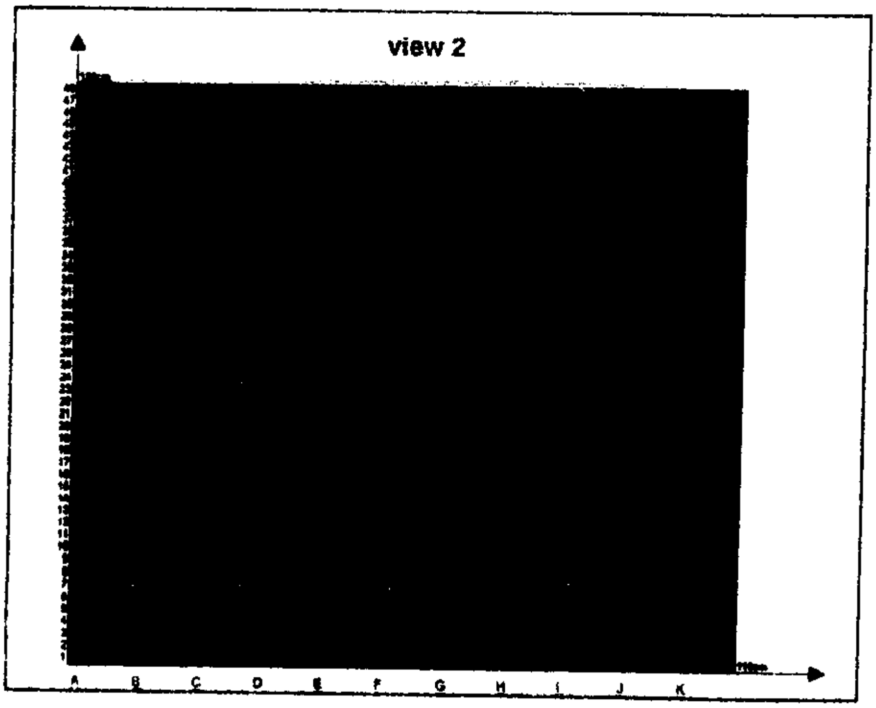
A DECREASE OF THE CORE THERMAL POWER RELEASE IS ASSUMED AS THE INITIATING PERTURBATION, WHICH, IN A FIRST APPROXIMATION, MODIFIES ABSORPTION CROSS SECTIONS ONLY AND GENERATES A REACTIVITY CHANGE IN THE SYSTEM WHICH HAS TO BE COMPENSATED BY CONTROL DEVICES (CONTROL CLUSTERS).



A B C D E F G H I J K
1 2 3 4 5 6 7 8 9 0 1
Plan1
Plan2
Plan oxy
Plan1 oz
Plan2 oz
Reflector
Fuel1
Fuel2
Control Rod 1
Control Rod 2

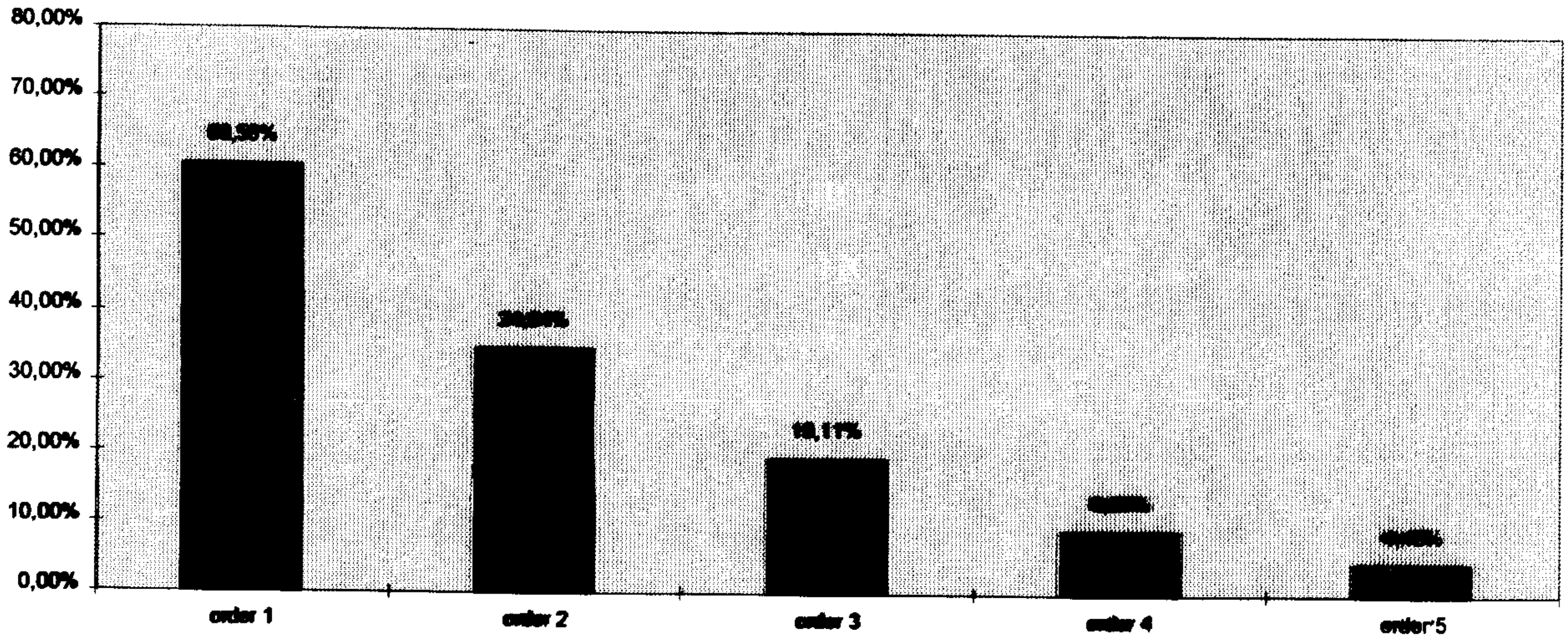
TEST



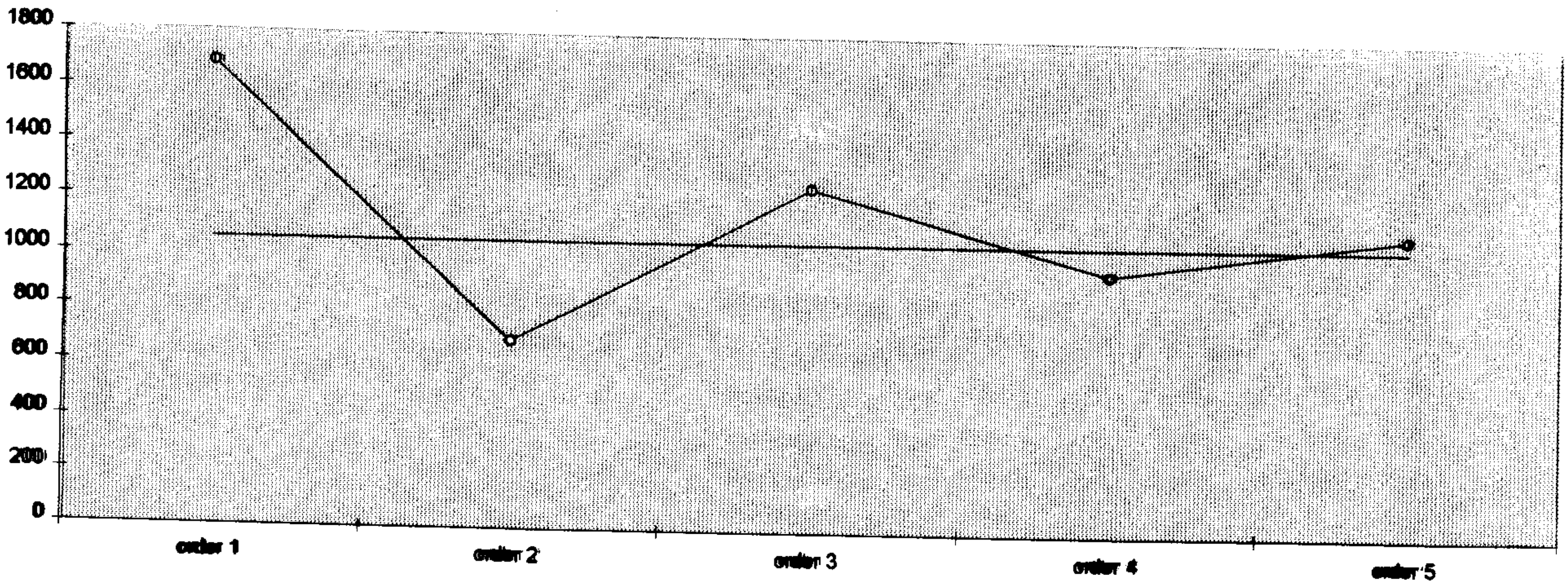


Reactivity (pcm)		Error
Reference Value	0	
Target Value	1054	
GPT order 1	1690	60,58%
GPT order 2	688	34,64%
GPT order 3	1254	19,12%
GPT order 4	958	8,98%
GPT order 5	1099	4,45%
Extrapolation Value	1046	0,80%

Reactivity error convergence

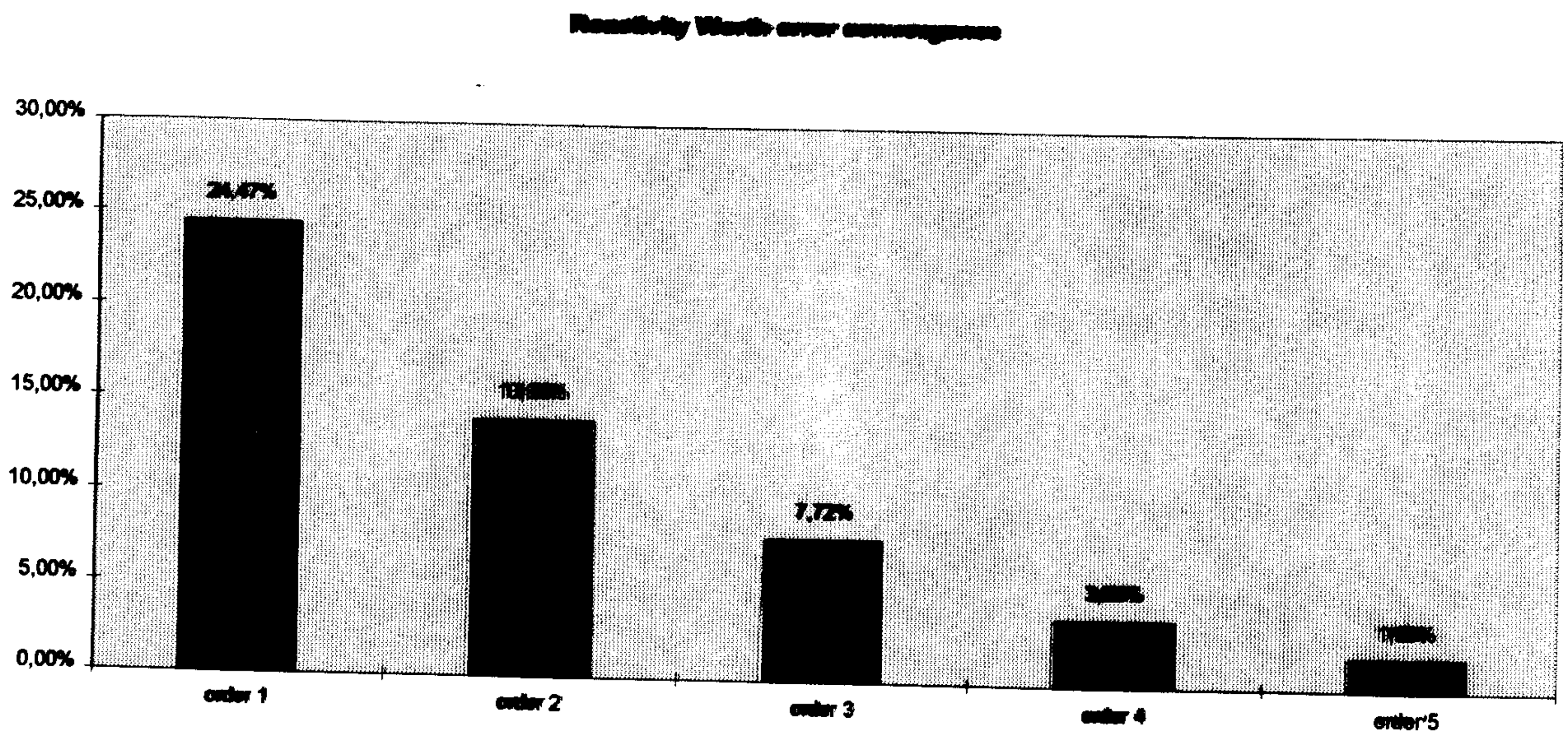


Reactivity GPT convergence



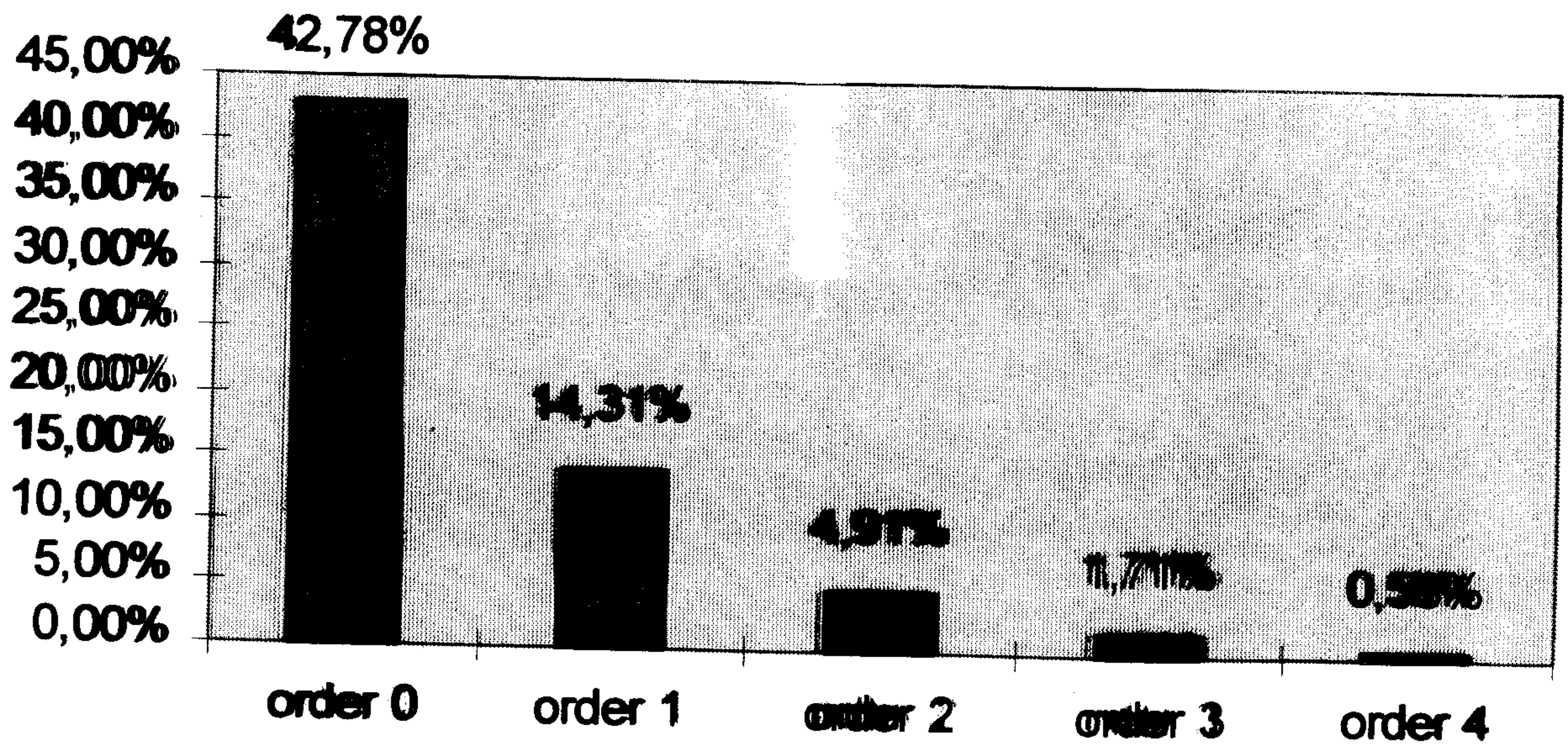
2

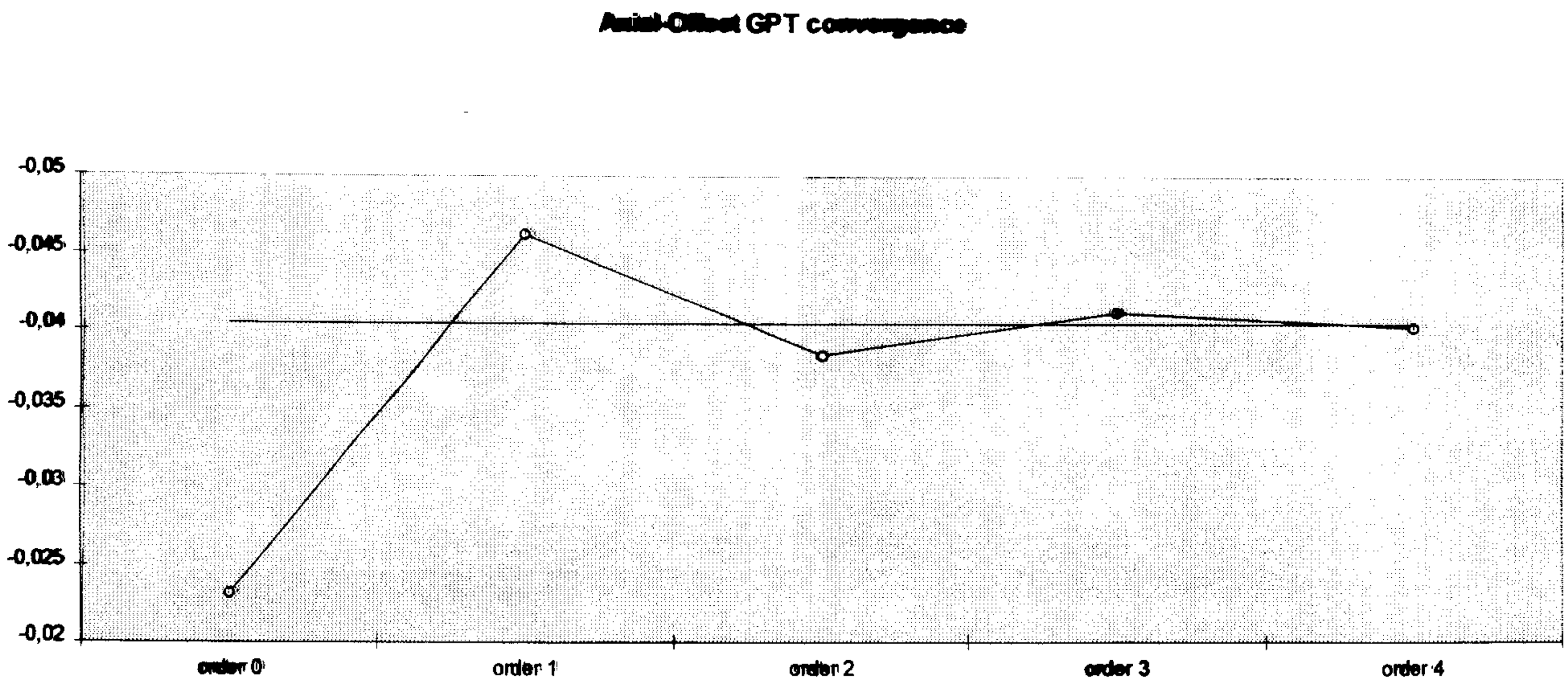
Reactivity Worth (pcm)		Error
Reference Value	3659	
Target Value	2607	40,35%
GPT order 1	1969	24,47%
GPT order 2	2971	13,99%
GPT order 3	2405	7,72%
GPT order 4	2701	3,63%
GPT order 5	2559	1,80%
Extrapolation Value	2613	0,27%


30,00%
25,00%
20,00%
15,00%
10,00%
5,00%
0,00%
24,47%
7,72%
order 1
order 2
order 3
order 4
order 5

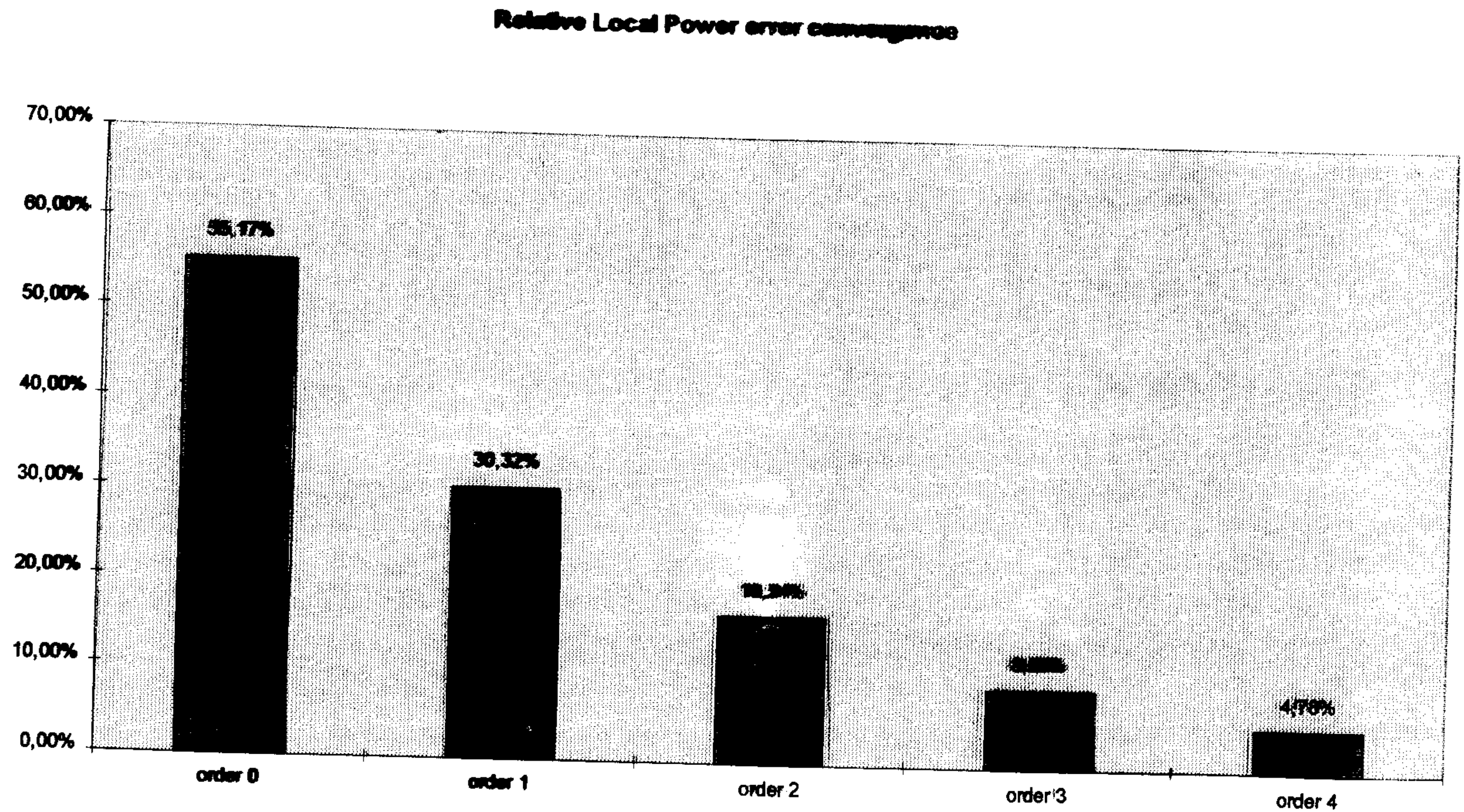
Axial Offset		Error
Reference Value	-0,0231327	
Target Value	-0,0404286	42,78%
GPT order 1	-0,0462136	14,31%
GPT order 2	-0,0384415	4,91%
GPT order 3	-0,0411215	1,71%
GPT order 4	-0,0401921	0,58%
Extrapolation Value	-0,0404988	0,17%

Axial-Offset error convergence



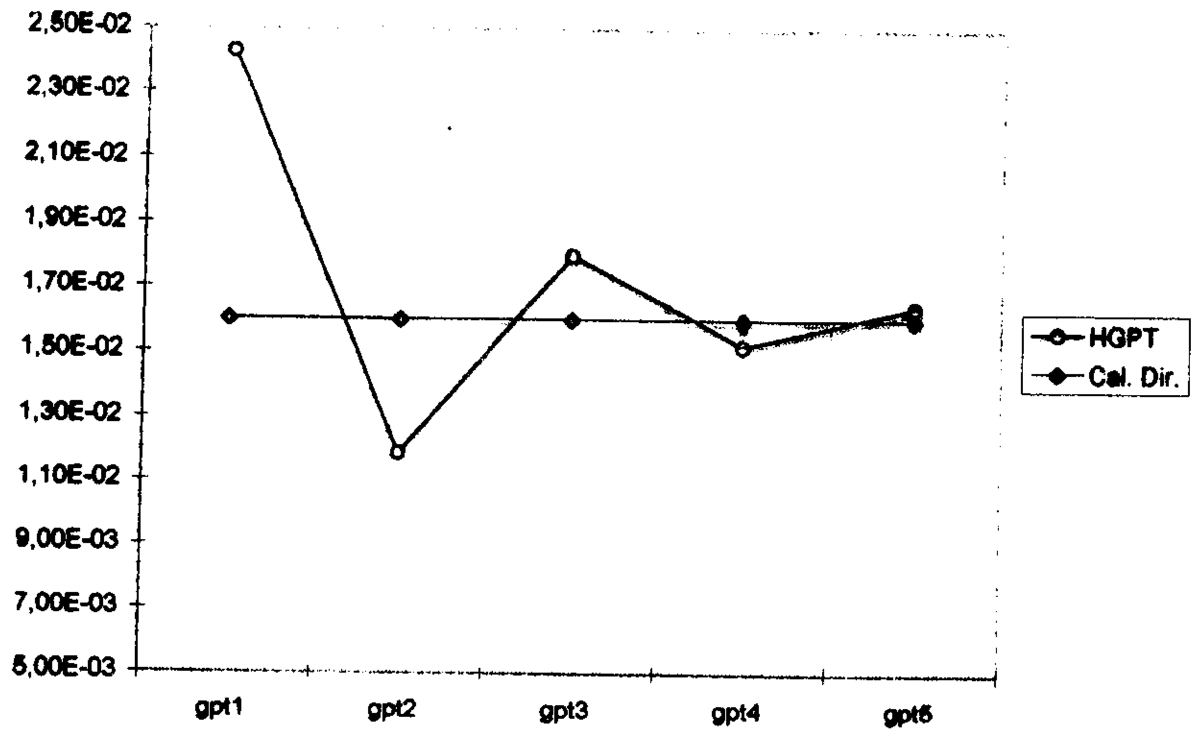

Axial-Offset GPT convergence
-0,05
-0,045
-0,04
-0,035
-0,03
-0,025
-0,02
order 0
order 1
order 2
order 3
order 4

Relative local Power		Error
Reference Value	0,00536841	
Target Value	0,00345967	55,17%
GPT order 1	0,00241041	30,33%
GPT order 2	0,00403218	16,55%
GPT order 3	0,00315063	8,93%
GPT order 4	0,00362505	4,78%
Extrapolation Value	0,00333702	3,54%

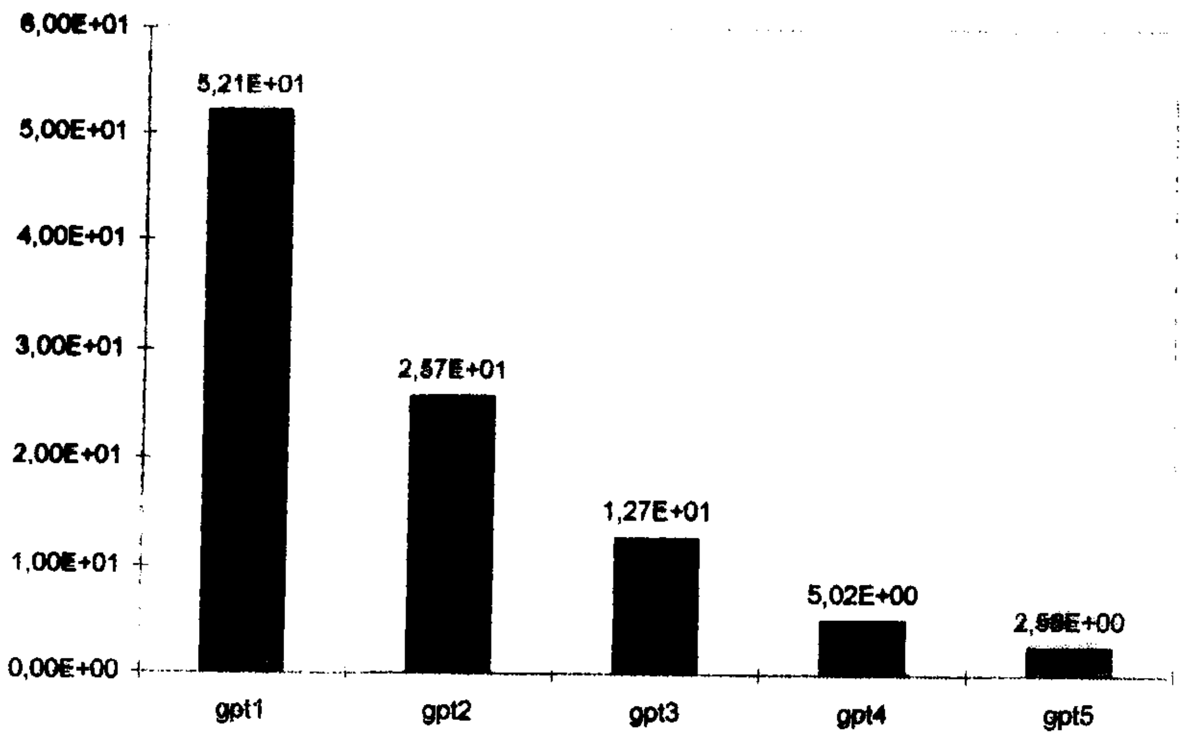

Relative Local Power error convergence
70,00%
60,00%
50,00%
40,00%
30,00%
20,00%
10,00%
0,00%
55,17%
30,32%
4,76%
order 0
order 1
order 2
order 3
order 4

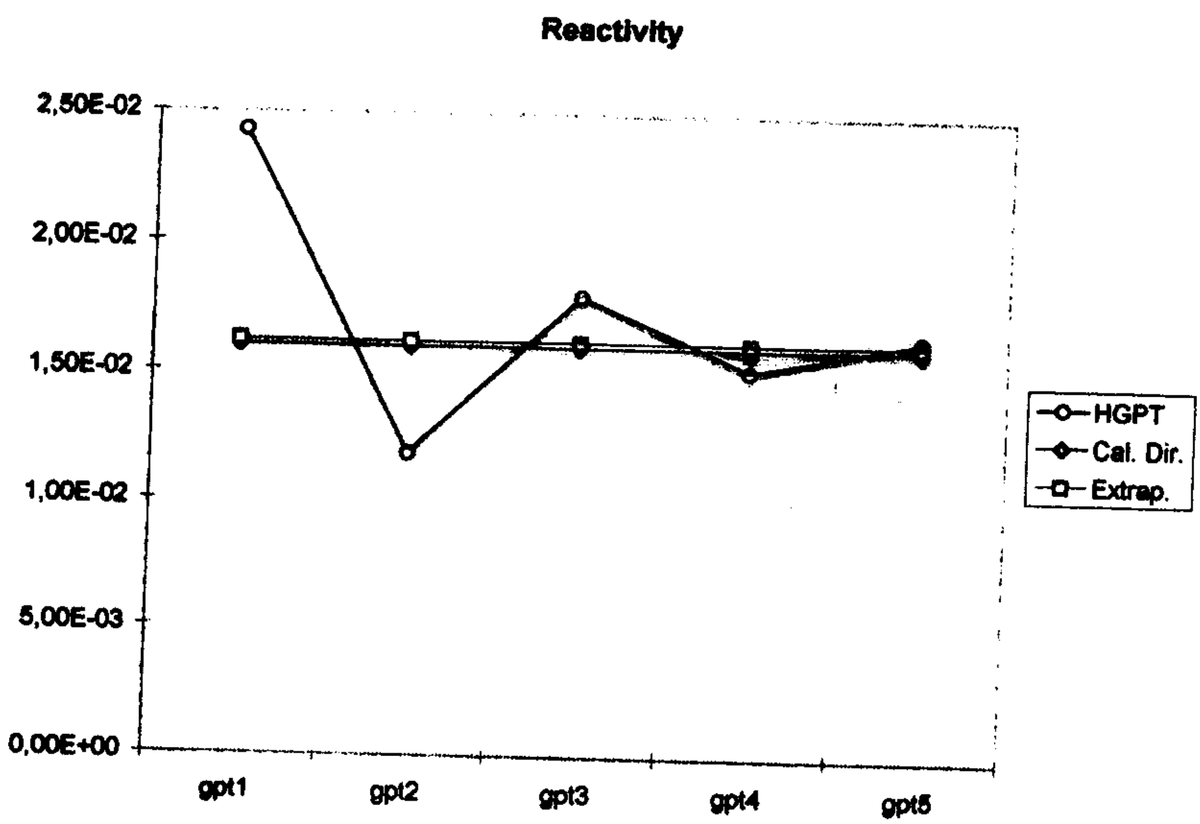
Reactivity (pcm)		Error
Reference Value	0	
Target Value	1,60E+03	
GPT order 1	2,43E+03	52,10%
GPT order 2	1,19E+03	25,70%
GPT order 3	1,80E+03	12,70%
GPT order 4	1,52E+03	5,02%
GPT order 5	1,64E+03	2,58%
Extrapolation Value	1,62E+03	0,88%

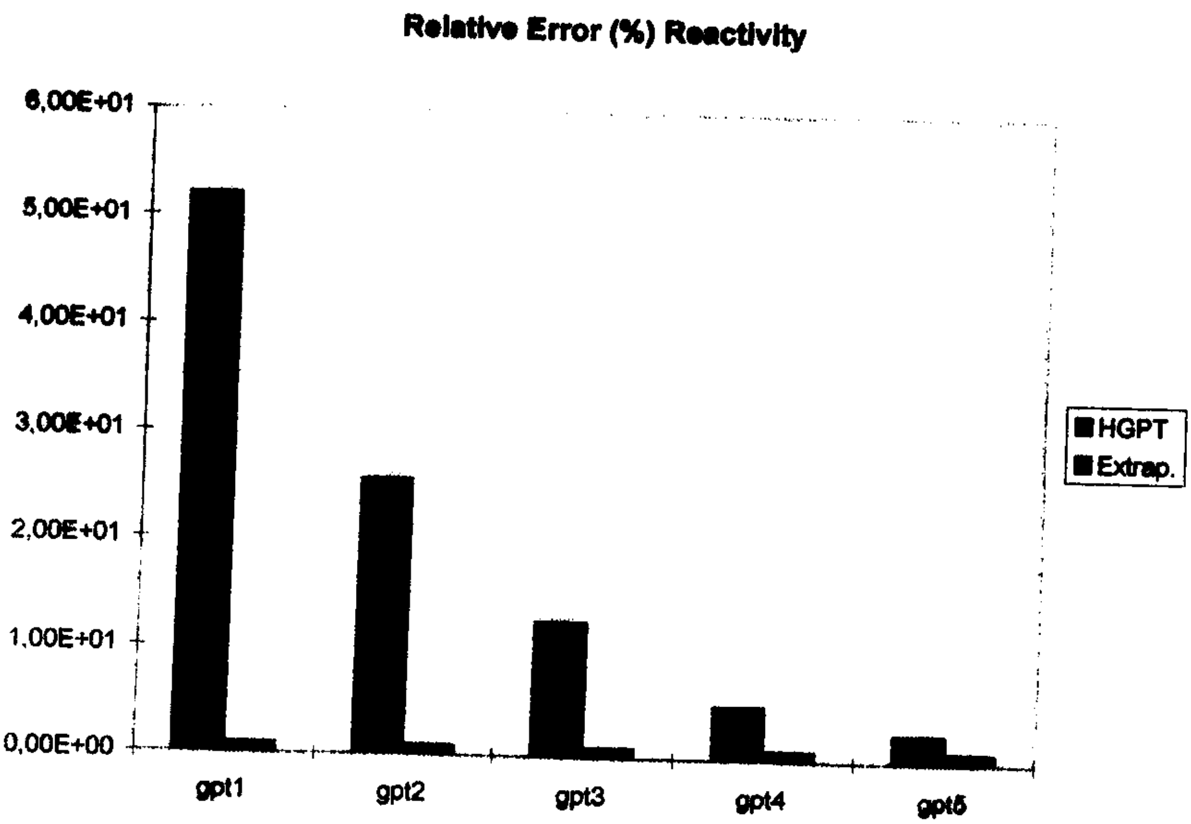
Reactivity



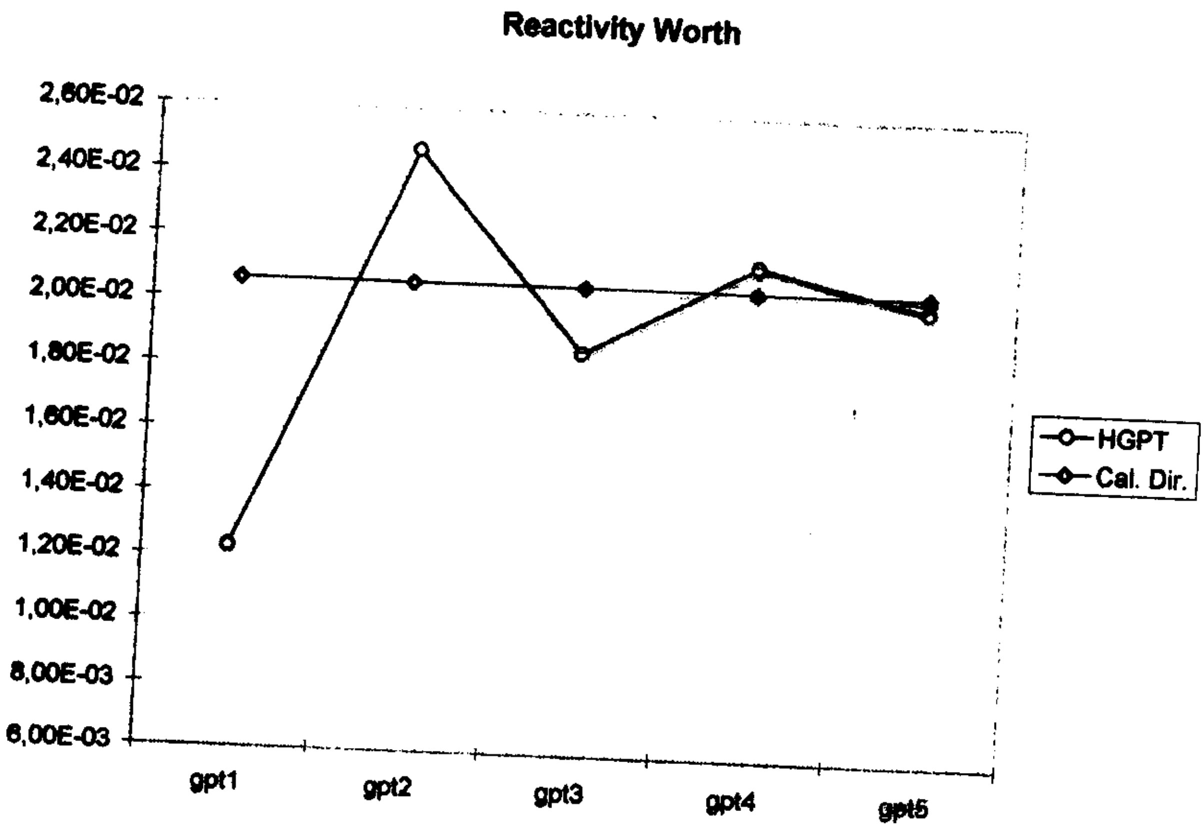
Relative Error (%) Reactivity

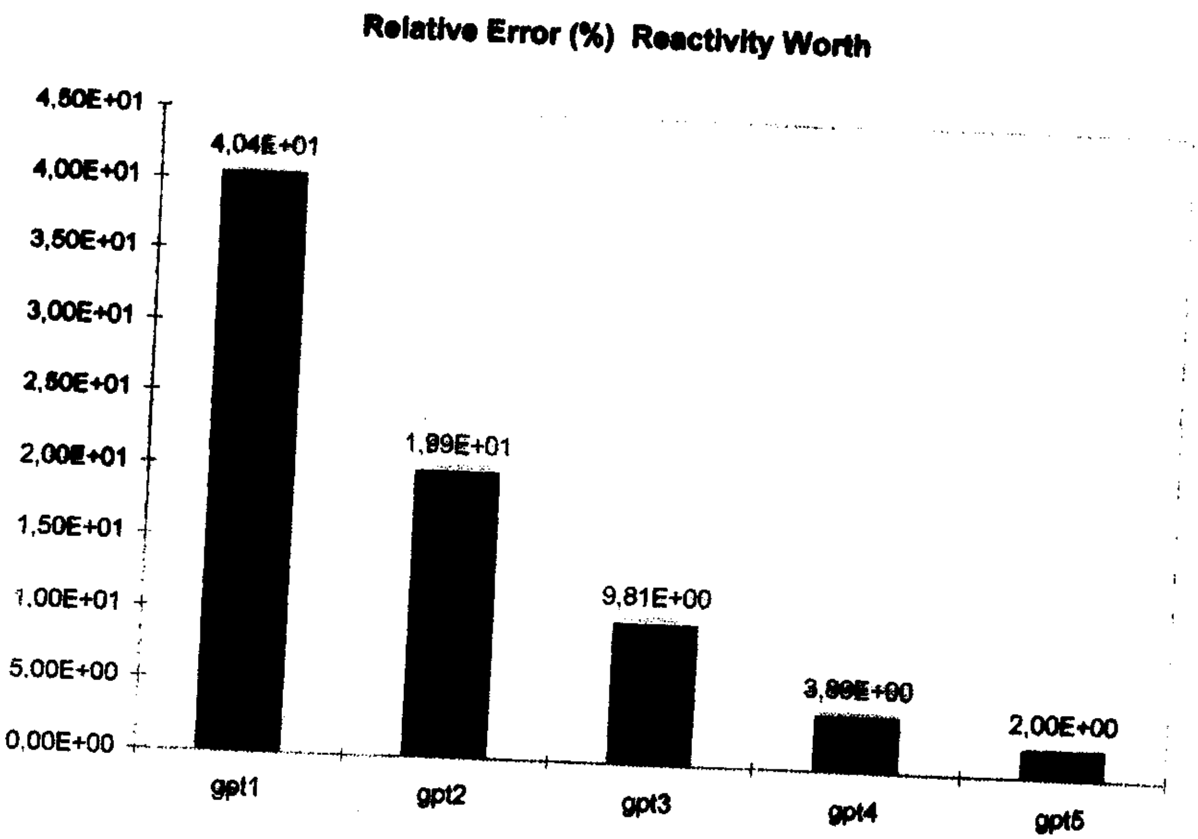


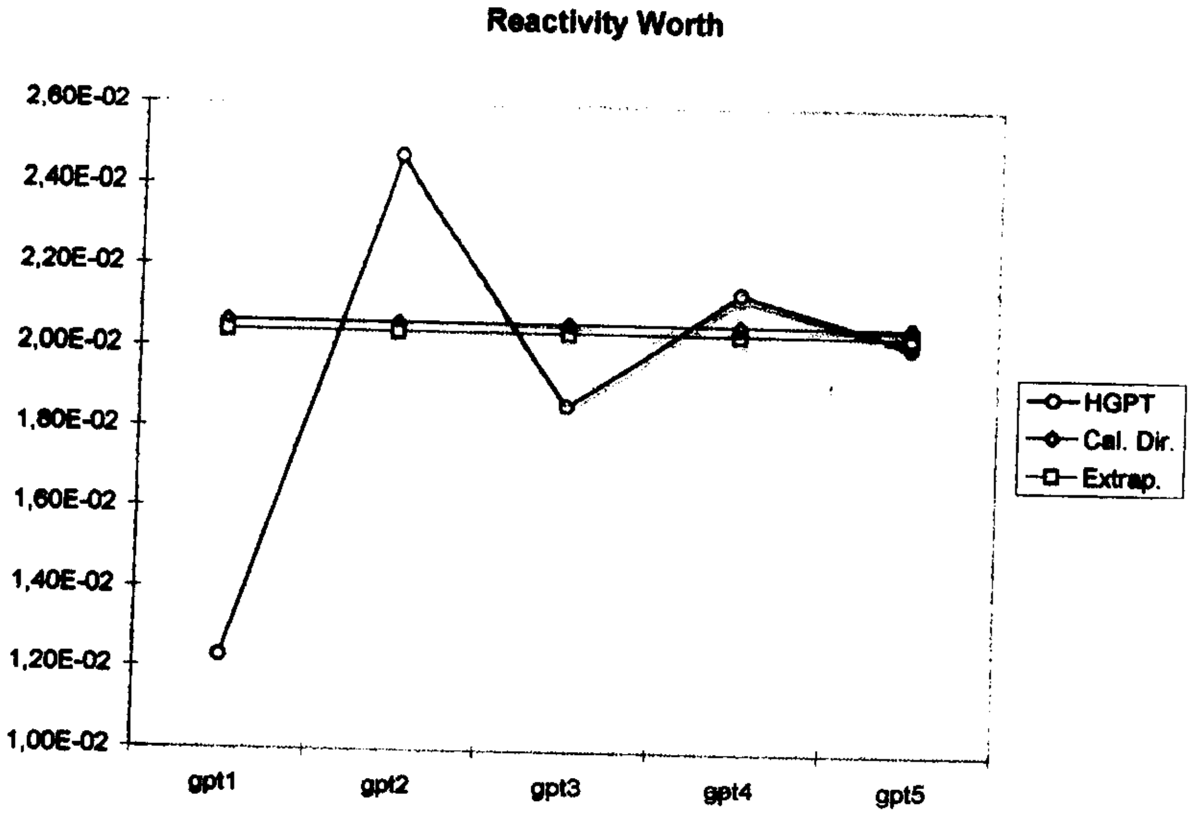

Reactivity
2,50E-02
2,00E-02
1,50E-02
1,00E-02
5,00E-03
0,00E+00
gpt1
gpt2
gpt3
gpt4
gpt5
HGPT
Cal. Dir.
Extrap.

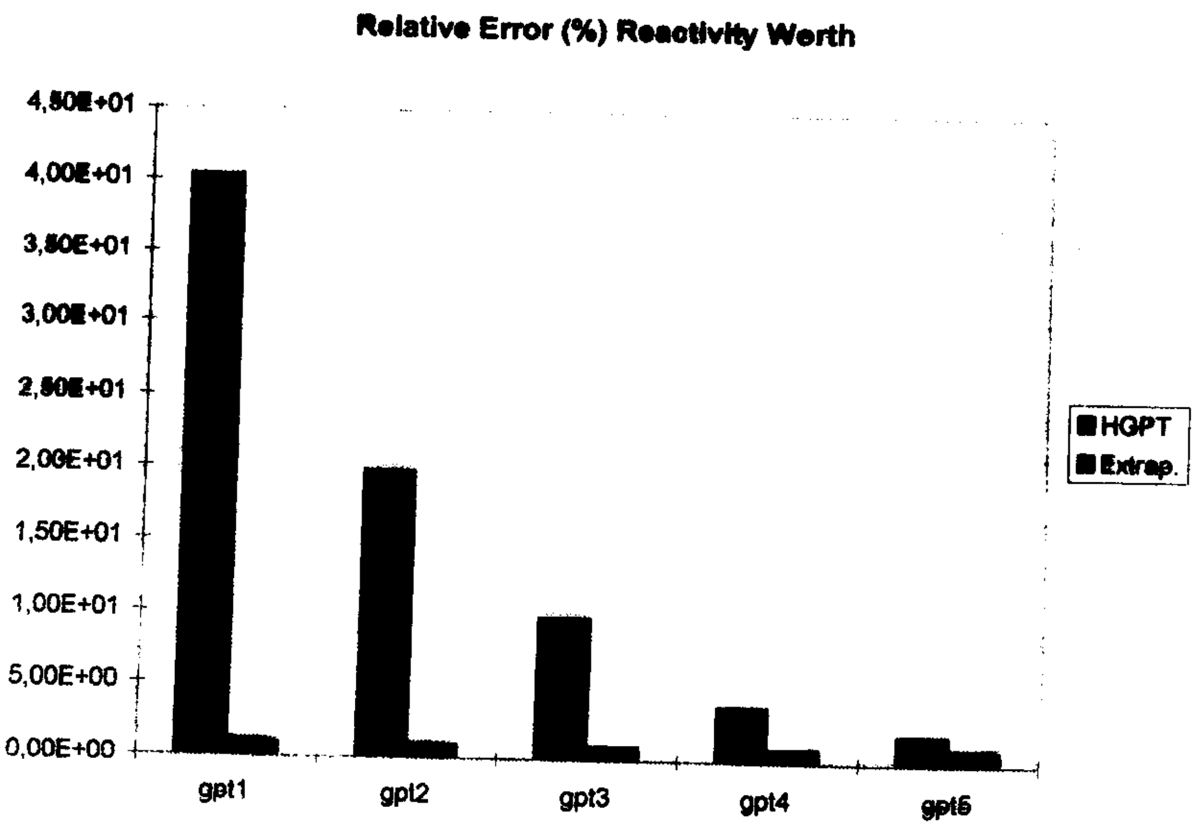

Relative Error (%) Reactivity
6,00E+01
5,00E+01
4,00E+01
3,00E+01
2,00E+01
1,00E+01
0,00E+00
gpt1
gpt2
gpt3
gpt4
gpt5
HGPT
Extrap.

Reactivity Worth (pcm)		Error
Reference Value	3,66E+03	
Target Value	2,06E+03	77,66%
GPT order 1	1,23E+03	40,04%
GPT order 2	2,47E+03	19,90%
GPT order 3	1,86E+03	9,81%
GPT order 4	2,14E+03	3,89%
GPT order 5	2,02E+03	2,00%
Extrapolation Value	2,04E+03	0,99%


Reactivity Worth
2,60E-02
2,40E-02
2,20E-02
2,00E-02
1,80E-02
1,60E-02
1,40E-02
1,20E-02
1,00E-02
8,00E-03
6,00E-03
gpt1
gpt2
gpt3
gpt4
gpt5
HGPT
Cal. Dir.

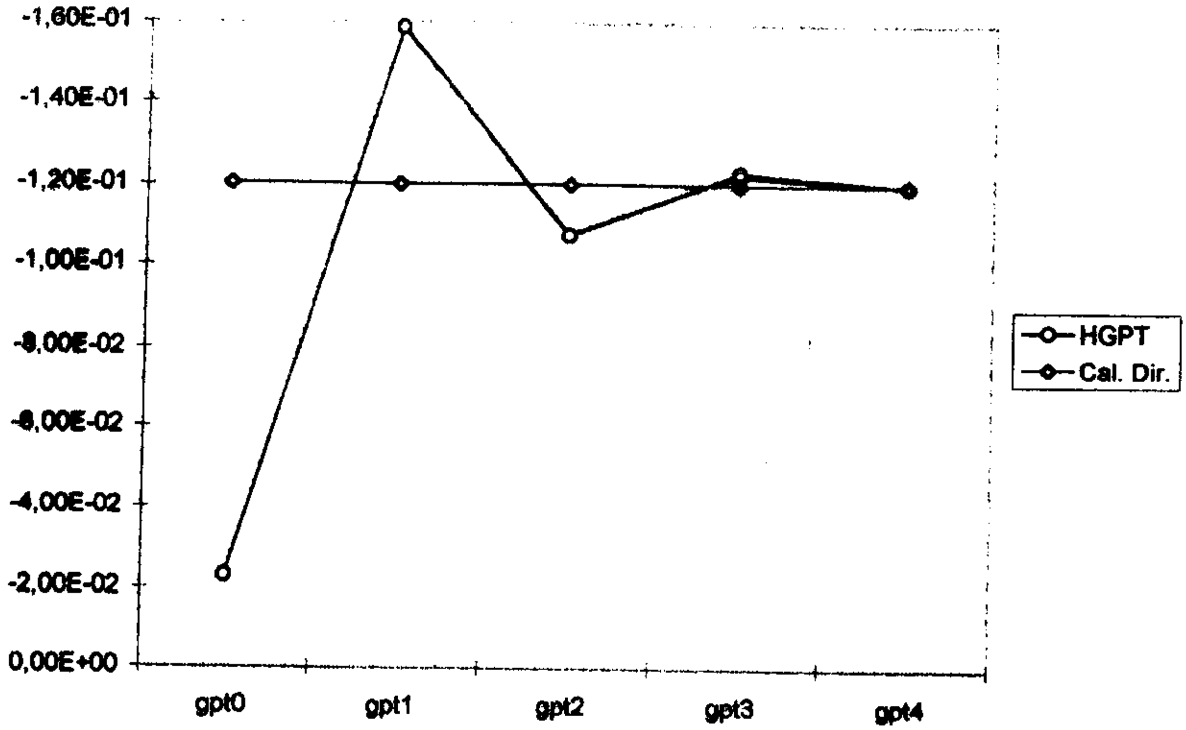

Relative Error (%) Reactivity Worth
4,50E+01
4,00E+01
3,50E+01
3,00E+01
2,50E+01
2,00E+01
1,50E+01
1,00E+01
5,00E+00
0,00E+00
4,04E+01
1,89E+01
9,81E+00
3,89E+00
2,00E+00
gpt1
gpt2
gpt3
gpt4
gpt5


Reactivity Worth
2,60E-02
2,40E-02
2,20E-02
2,00E-02
1,80E-02
1,60E-02
1,40E-02
1,20E-02
1,00E-02
gpt1
gpt2
gpt3
gpt4
gpt5
HGPT
Cal. Dir.
Extrap.

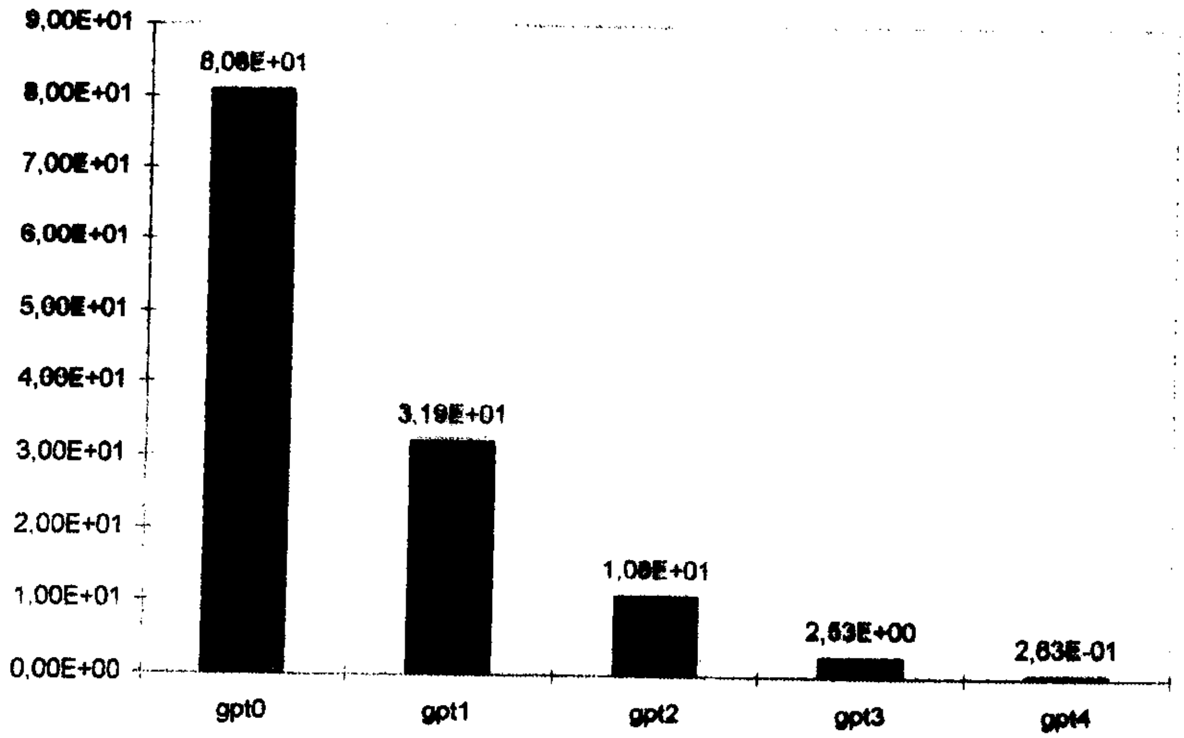

Relative Error (%) Reactivity Worth
4,50E+01
4,00E+01
3,50E+01
3,00E+01
2,50E+01
2,00E+01
1,50E+01
1,00E+01
5,00E+00
0,00E+00
gpt1
gpt2
gpt3
gpt4
gpt5
HGPT
Extrap.

Axial Offset		Error
Reference Value	-2,31E-02	
Target Value	-1,20E-01	80,80%
GPT order 1	-1,59E-01	31,90%
GPT order 2	-1,07E-01	10,80%
GPT order 3	-1,23E-01	2,53%
GPT order 4	-1,20E-01	0,26%
Extrapolation Value	-1,14E-01	5,27%

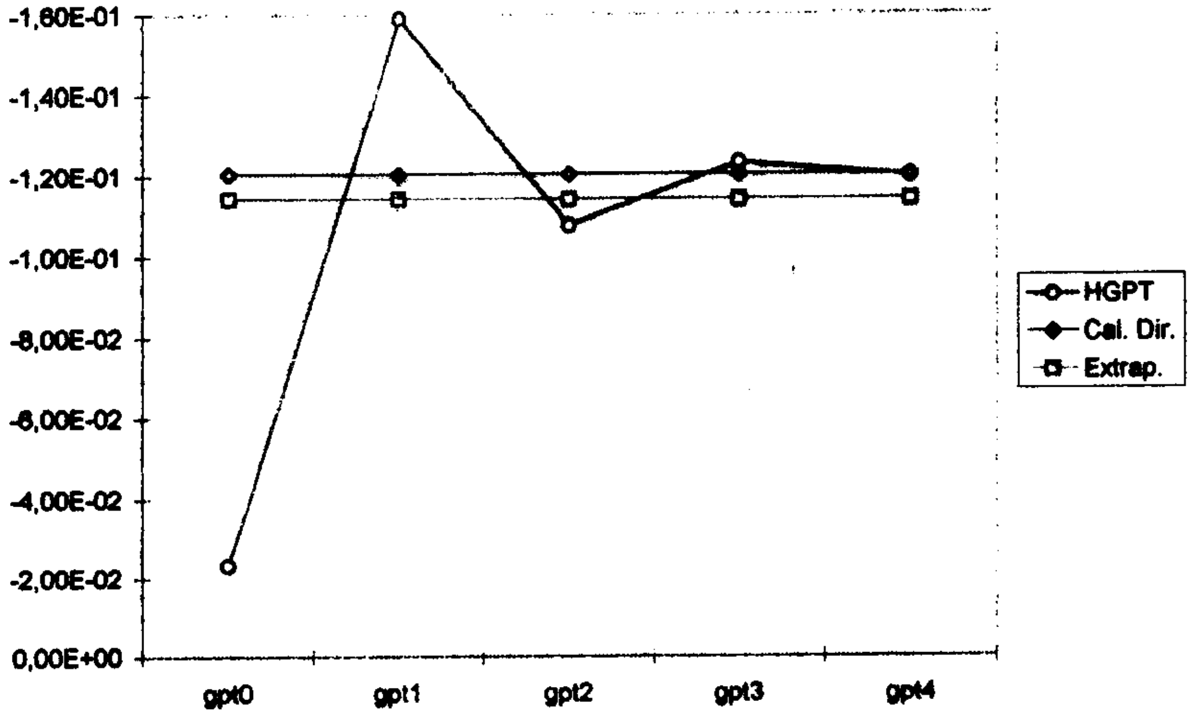
Axial Offset



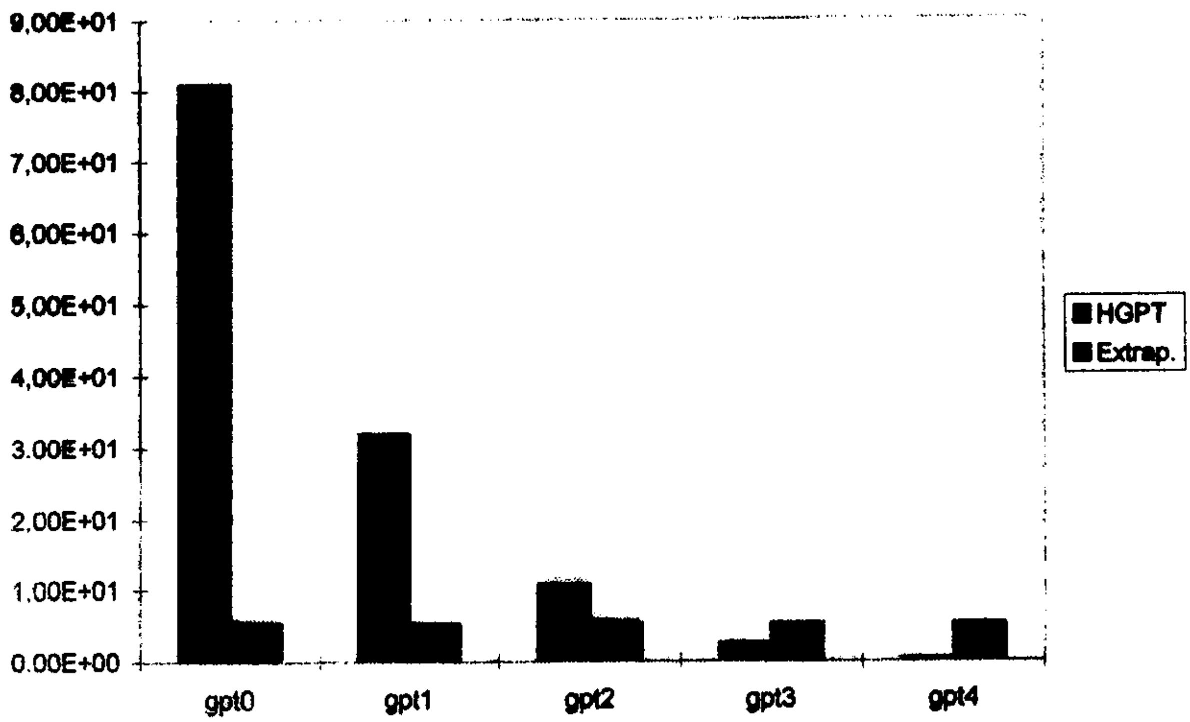
Relative Error (%) Axial Offset



Axial Offset

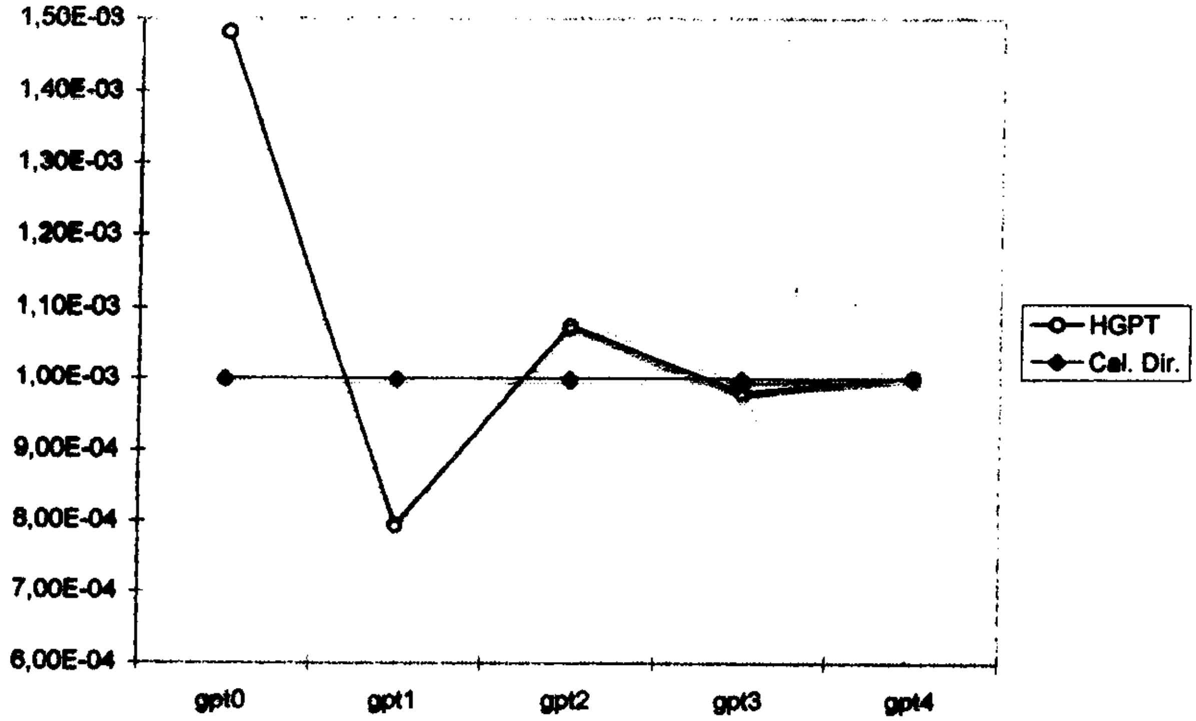


Relative Error (%) Axial Offset

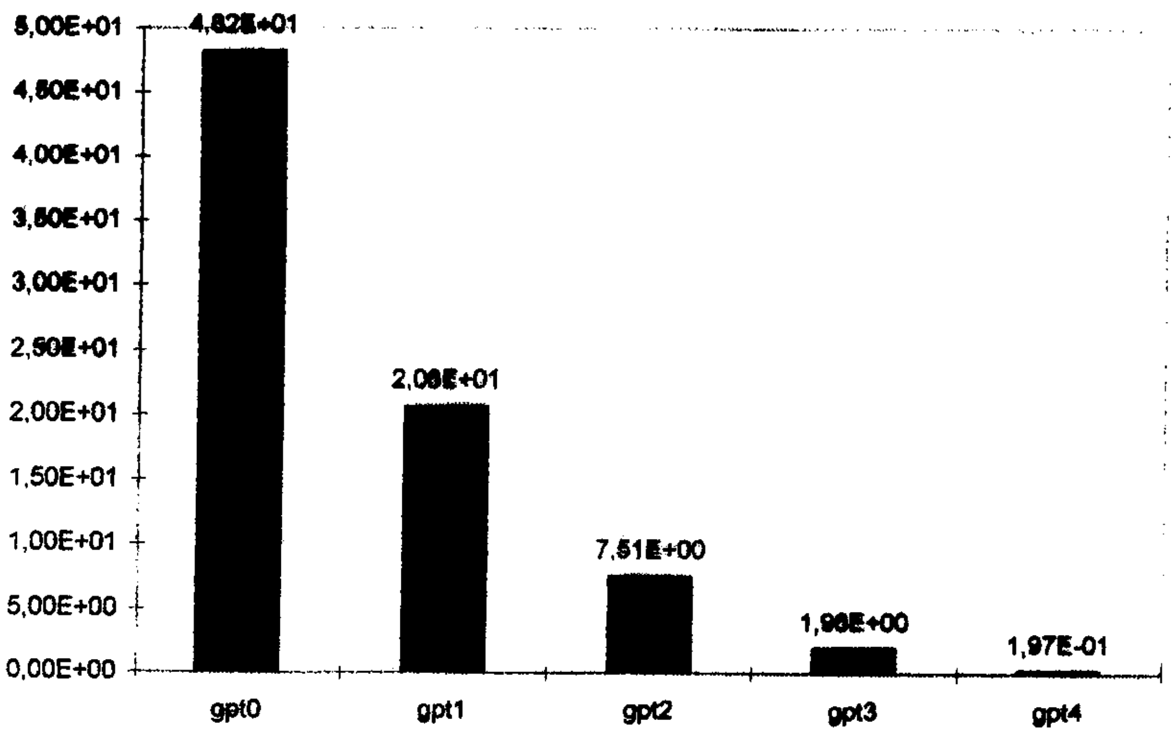


Relative local Power		Error
Reference Value	1,48E-03	
Target Value	1,00E-03	48,20%
GPT order 1	7,94E-04	20,60%
GPT order 2	1,07E-03	7,51%
GPT order 3	9,80E-04	1,96%
GPT order 4	1,00E-03	0,20%
Extrapolation Value	1,02E-03	2,12%

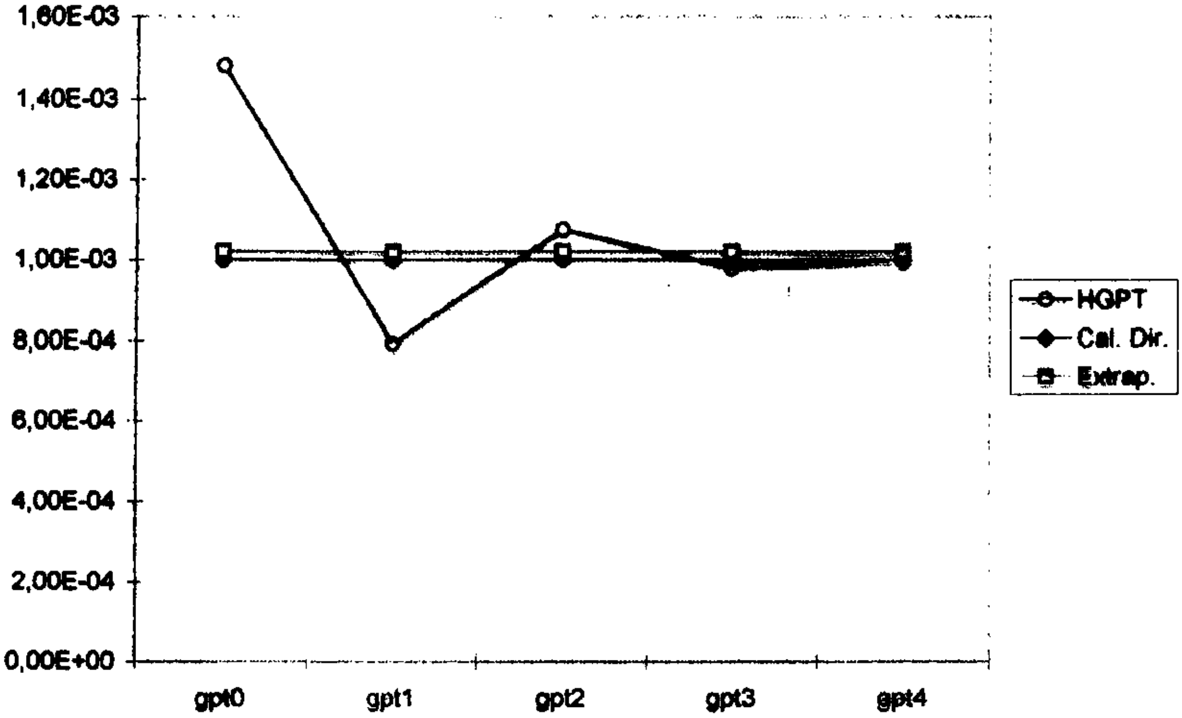
Local Power



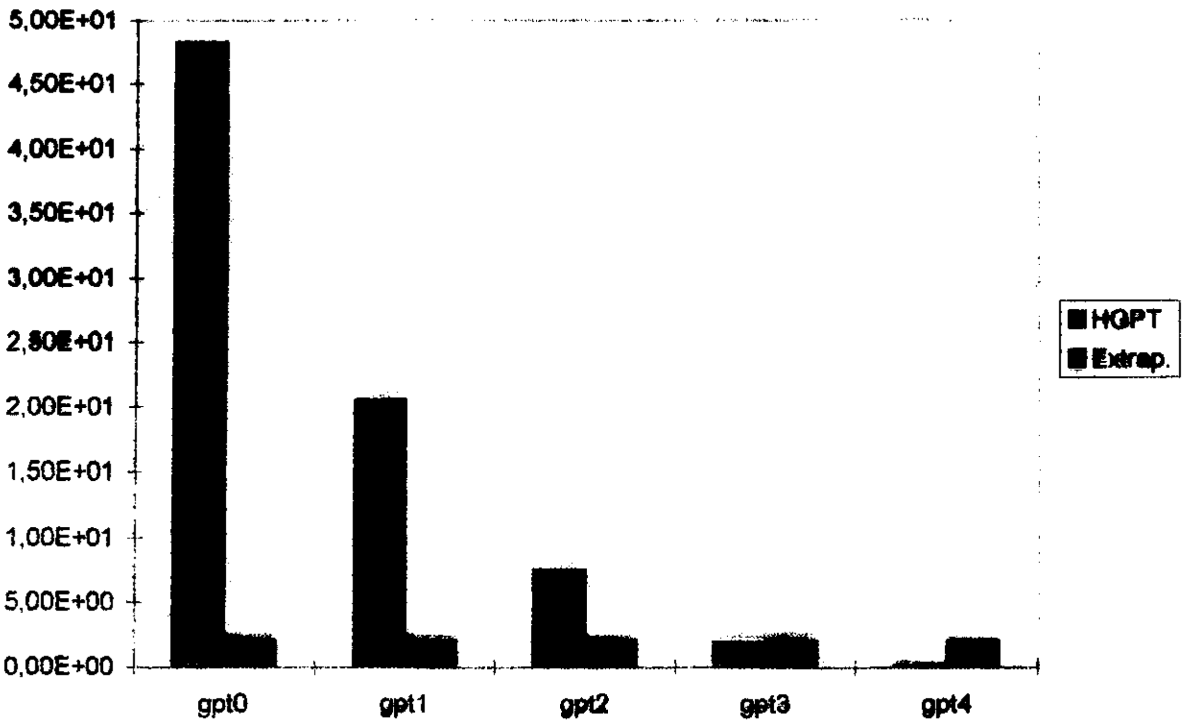
Relative Error (%) Local Power



Local Power

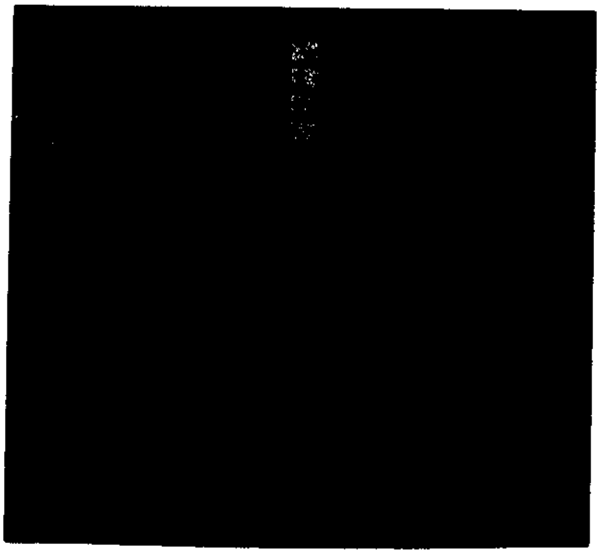


Relative Error (%) Local Power

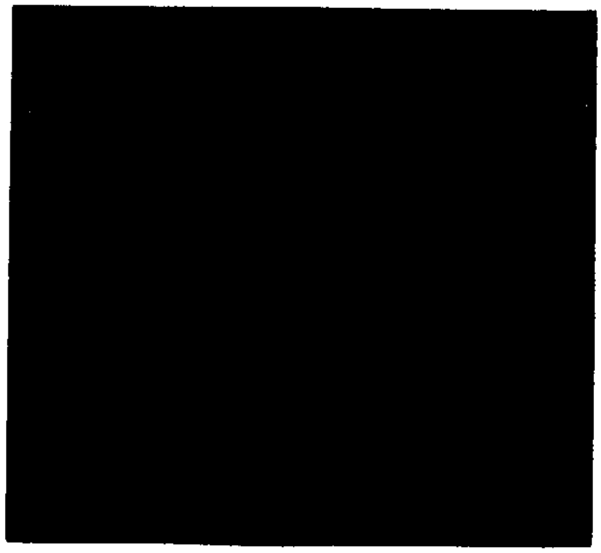


	Av. Error Third Order	Disp. 2 sigma	Av. Error Forth Order	Disp. 2 sigma	Av. Error Extrap. Value.	Disp. 2 sigma
Axial Offset	3,06%	6,15%	1,12%	1,68%	1,08%	3,18%
Relative Local Power	4,36%	9,68%	2,01%	4,39%	1,79%	2,95%
Reactivity	3,74%	8,10%	1,78%	3,91%	0,79%	0,56%
Reactivity Worth	0,73%	1,99%	0,40%	0,77%	0,13%	0,28%

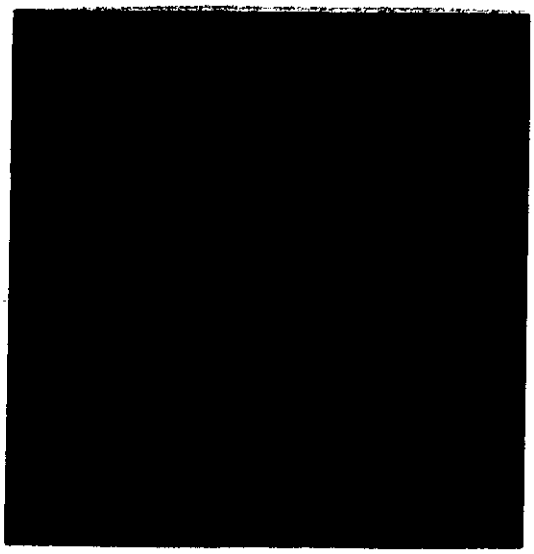
Configurazione delle barre di controllo



Sez 1



Sez 2



Sez 3

Fig 2

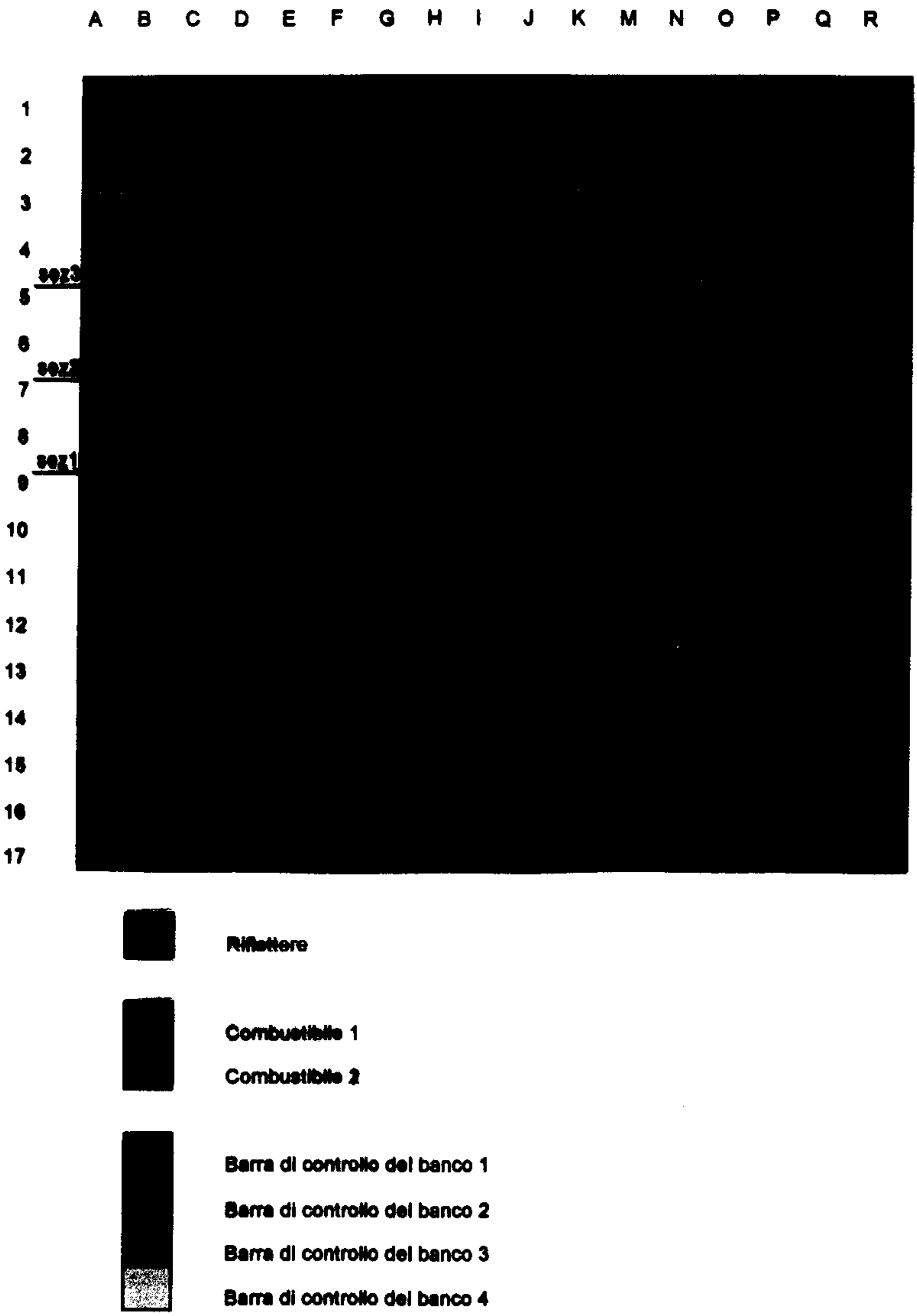

A B C D E F G H I J K M N O P Q R
1
2
3
4
sez3
5
6
sez2
7
8
sez1
9
10
11
12
13
14
15
16
17
Riflettore
Combustibile 1
Combustibile 2
Barra di controllo del banco 1
Barra di controllo del banco 2
Barra di controllo del banco 3
Barra di controllo del banco 4

Fig 1

MAIN CONCLUSIONS

THE HGPT SOLUTION, WHEN COMPUTED IN FINITE ELEMENT MIXED - DUAL APPROXIMATION, IS SENSITIVE TO EXPANSION ORDER, BUT IT FITS REFERENCE VALUE WITHOUT ANY SIGNIFICANT LOSS IN RELATIVE PRECISION.

THE EXISTENCE OF A BOUNDED CONVERGENCE RANGE ENABLES DEFINITION OF AN EXTRAPOLATION FORMULA, WHICH ACCOUNTS FOR HIGHER ORDER CONTRIBUTIONS WITHOUT EXPLICITLY COMPUTING THEM.

USE OF A LIMITED NUMBER OF IMPORTANCE FUNCTIONS (FIRST ORDER) WITHIN THE EXTRAPOLATION FORMULA ENABLES APPRECIATING THE ASYMPTOTIC SOLUTION WITH A PRECISION WHICH IS ALWAYS BETTER THEN THE SECOND ORDER.

COEFFICIENTS IN THE EXTRAPOLATION FORMULA ARE SLOWLY VARYING FOR SMALL PERTURBATIONS, WHEN CONTRIBUTION OF HIGHER ORDER TERMS IS NOT SIGNIFICANT, AND ARE ROUGHLY CONSTANT FOR BIG PERTURBATIONS WHEN THEIR SHARE IS IMPORTANT.

The OAS - Operator Aid System

- Work performed on HGPT in the framework of the above-mentioned venture:
  - contributes to SAP development,
  - gives a very useful tool for physical analysis (sensitivity studies),
  - contributes to on-line adjustment of the model.

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The OAS - Operator Aid System

- Work underway:
  - definition of a prototype of a 3D on-line control device (PIMS),
  - implementation of several SAP features inside the prototype of 3D on-line control device (PIMS).

The OAS - Operator Aid System

- The OAS main function inside the 3D on-line control device (PIMS) is:
  - to evaluate alarmes (LCO) as a function of the actual conditions of the reactor core.

The OAS - Operator Aid System

- To fit this objective, the OAS computes on-line, without any iteration:
  - the shut-down safety margin,
  - the ejected control-rod reactvity worth,
  - the rod drop reactivity worth.

The OAS - Operator Aid System

- Implementation of OAS features in the 3D on-line (PIMS):
  - adoption of HGPT methodology and extrapolation formulae,
  - HGPT development in the NEM environment,
  - work to be done in the framework of the thesis.

The OAS - Operator Aid System

- HGPT development in the NEM environment:
  - features of the NEM computational procedure allow defining a finite difference adjoint flux which meets all requirements of HGPT:
    - the eigenvalue is conserved,
    - the orthogonality conditions are satisfied,
    - classical HGPT formulae hold on.

The OAS - Operator Aid System

- Demonstration has already been done for CPT.
- The principles have been presented at the M&C'99 in Madrid and are summarized here.

The OAS - Operator Aid System

- Implementation of HGPT features in NEM environment : Excerpts from the Madrid Presentation.

MC '99 Madrid

New Developments in Nodal Perturbation Theory for Reactor Operation

by

G.B. Bruna, P. Girieud, A. Sargeni
FRAMATOME

FRAMATOME

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New Developments in Nodal Perturbation Theory for Reactor Operation

- **Summary :**
  - 1) Historical Background,
  - 2) The NEM Adjoint Methodology
    - Features
    - Consequences,
  - 3) Proposed Solution et Applications,
  - 4) Work Underway,
  - 5) Conclusion

- **1) Hystorical Background**

- Load-follow, currently adopted in French nuclear power plants, needs to change frequently control-cluster positions and boron concentration.

- These changes must be made to keep operational ande safety parameters inside well-defined ranges.

- Perturbation theory can show-up a precious tool for reactor control, because it allows :
  - To help forecasting variations of operation and safety parameters (axial offset, shutdown margins, reactivity) when control parameters change,
  - To contribute defining range of control parameters.

- Framatome, Enea, Cea and Bologna University developed application of high order perturbation theory (HGPT) to reactor control problems,

- Adopting a suitable extrapolation procedure, 1th order HGPT expansion (perturbation independent) was corrected as to obtain 4th order equivalent results,

- Such developments were implemented in Minos-Cronos (a mixed dual finite-element code) getting excellent results.

- For many practical reasons, it is now worth to up-date Framatome computational chain SCIENCE [including APOLLO2 (cell code) and SMART (core code)] with these computational features for 3D on-line purposes.

- **2) The NEM Adjoint Methodology**

- SMART is a NEM (Nodal Expansion Method) code which is not discretization invariant as finite-difference ones are,

- Thus, problems arise on how to compute an adjoint flux, which allows to maintain the HGPT expansion unchanged

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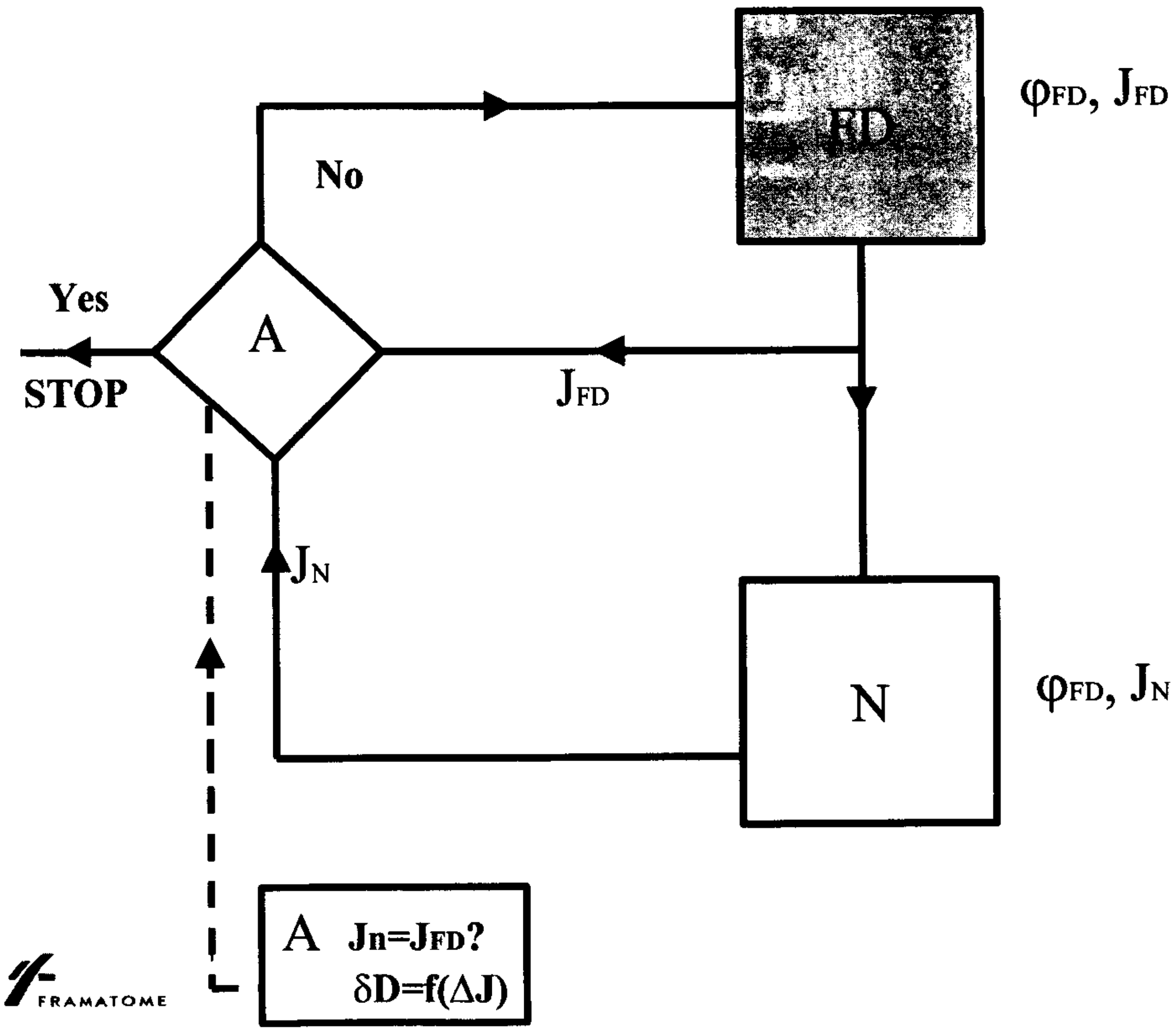
- The NEM scheme consis[illegible]
  - a finite-difference (FD) module to compute the flux,
  - a nodal module, using Assembly Discontinuity Factors (ADF) and a polynomial expansion of the flux, to compute curren[illegible]

- Link between the two modules in SMART is made by changing FD diffusion coefficients iteratively in such a way as to obtain a FD current which is congruent to the nodal current.


FD
φFD, JFD
No
Yes
A
STOP
JFD
JN
N
φFD, JN
A Jn=JFD?
δD=f(ΔJ)

- Kobayashi (1998) has shown that it is possible to compute a 'consistent' adjoint flux, using a nodal code, putting discontinuity on the adjoint currents instead of the adjoint flux,
- 'Consistent' means here that the adjoint flux computed that way has the same eigenvalue as direct flux.

- **PROBLEM**
  - classical HGPT expansion formulae as

$$\rho = \frac{<\varphi^*,(\delta A - \lambda \delta F)\varphi' >}{<\varphi^*, F'\varphi >}$$

  - hold no more,
  - Expression of reactivity changes to take into account ADF, loosing, that way, the linearity property which allows to split the total variation into a sum of cross-section dependent terms.

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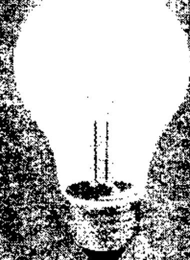
- **3) Proposed Solution and Application**



- **IDEA!**
  - In NEM scheme, a coupling holds between a FD module and nodal module.
  - In the final iteration before convergence FD module describes a system which satisfies the right balance equation in every node, and **that is exactly what we need !**

- **APPLICATION**
  - An adjoint flux computed starting from this converged system obviously has the same eigenvalue as the direct flux,
  - Conventional reactivity formulae derived from HGPT theory hold unchanged.

- **RESULTS**
  - A wide series of applications was made,
  - All the tests performed showed up fully satisfactory,
  - A selection of results is presented in the paper.

- **4) Work Underway**

- **Assumption :** Generalized HGPT importance functions can be computed on the same theoretical basis.

- **Application :** Work is underway, now, but significant achievements have already been obtained.

- **5) Conclusion**

- A suitable solution to the problem of keeping HGPT in a NEM environment is proposed,

- Excellent results have been already obtained for reactivity.

- **5) Conclusion ctnd.**
- Generalization to any other funtionnel is underway,
- Application to reactor control is scheduled next year in the framework of development of a 3D on-line control device.

The OAS - Operator Aid System

- Now, demonstration is to be extended to:
  - generalized importance functions,
  - extrapolation formulae.

The OAS - Operator Aid System

- A Thesis work in collaboration with ENEA and University of Rome is starting now. It should enable us to complete theoretical work and perform first applications.

The OAS - Operator Aid System

- Thesis framework and objectif:
  - acquire knowledge of:
    - sensitivities, via direct and HGPT calculations,
    - SCIENCE (NEMO) computational package,
    - previuos work on SAP:
      - theoretical items (development of HGPT and extrapolation formulae),
      - applications.

The OAS - Operator Aid System

- Thesis framework and objectif (cntd):
  - to demonstrate feasibility of a conceptual design of OAS (SAP device) based on NEM discretization, HGPT methodology and extrapolation formulae,
  - to perform a first-hand application to a real core case.